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**STEEL ALLOY AND METHOD OF MAKING SAME**  
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This invention relates to the manufacture of steel and more particularly to improved steel alloys and products thereof, and procedure for making the same, which have unusual strength and toughness and are susceptible of ready fabrication, by forming or welding, without loss of the desired mechanical properties. More specifically the invention is concerned with compositions that may be classified as low-alloy steel, containing substantially less than 1% carbon, but designed and prepared, as will be explained below, in a manner to attain new and exceptional results, and to attain such results without requiring relatively large amounts of expensive alloying ingredients. Moreover the products of the invention are characterized by unusual cleanliness of the alloy, specifically in an essentially complete absence of non-metallic inclusions.

Most importantly, because of various features, as explained below, including the above factor of cleanliness and the absence of a number of heretofore unavoidable components, the mechanical properties of the metal (e.g. after heat treatment) are very notably superior to those of prior steels of similar type and purpose. The invention, moreover, provides a product having exceptional uniformity of composition and structure, with a remarkable absence of internal notches, cracks and the like. In consequence, for a given purpose it is generally safe to employ no more than a minimum quantity of metal pursuant to requirements of strength in the fabricated structure; this aspect of the alloy is particularly significant where weight is critical and it is undesirable to allow extra weight as a factor of safety.

In a specific but important sense the present improvements have the object of providing a steel with a yield strength in the range of 100,000 to 175,000 p.s.i. or more, a tensile strength in the range of 115,000 to 190,000 p.s.i. or more, and a ductility, expressed as percent reduction in area, of between 40% and 80%, the steel being such that it can achieve these properties by and after heat treatment. The steel is characterized by unusual qualities of toughness including high impact resistance, a further feature of preferred embodiments being that the superior mechanical properties, especially toughness, are exhibited over a relatively wide temperature range, notably extending to quite low temperatures.

A primary and very great advantage of the alloys, in the carbon range from about 0.15% up to about 0.35%, is weldability in the heat treated condition. Thus in one specific sense the invention extends to plate or the like, or more generally, rolled or forged products having thickness, say, of 1/4 inch and upwards, which can be fully heat treated to the required properties and which can thereafter be fabricated by welding (as in shipbuilding or similar construction) without significant impairment of strength and toughness.

Heat treatment of the alloys is in general effected in conventional ways, especially including a quench from a high temperature, e.g. 1500° F. and above, and then tempering at any desired temperature but with special advantage (as explained below) in a range upwards of 1000° F., references herein to heat treatment being thus generally employed with the usual meaning of conventional operations for developing desired properties of strength and toughness, and also, ordinarily, hardness. As a rule, heat treatment of the steel is performed after

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any desired forming, and may comprise appropriate operations embracing one or more, and in many cases all, of the known steps of normalizing, austenitizing and tempering.

The metal, from the ingot, can be worked or deformed in any usual manner, for instance by rolling (e.g. hot rolling), forging or the like, and may be produced as plate, sheet, strip, rod, bar or other suitable stock, or forgings of desired shape. Forming, e.g. as may be needed for fabrication, is ordinarily effected in the annealed condition and can involve bending, stamping, pressing, drawing, punching, or the like. Thus forming, especially all drastic forming, is done before full heat treatment; a suitable operation being to carry out the forming of plate, sheet or the like after an anneal at about 1400° F. with controlled cooling to about 1000° F. followed by air cooling to ambient temperature. When well annealed, the steel forms readily in the cold. Some operations, such as cutting, punching and in some cases (at the lowest carbon values) mild forming, may be performed after heat treatment. As explained above, in the case of alloys in the lower carbon range, welding may be done after as well as before the article is heat treated, whereas in general the improved alloys of about 0.35% to about 0.60% carbon require welding in the annealed state, as in the case of forming, and before heat treatment.

Particular features of the alloy include an unusually low content of oxygen, and also of hydrogen and nitrogen, while at the same time there is a similarly unusual freedom from non-metallic inclusions as well as unusually low inclusions of non-metallic elements such as phosphorus and sulfur. It is believed that alloys of the present general type have not heretofore been produced with this low order of concentration of the impurities or inclusions stated. For example, attempts to reduce correspondingly the amount of oxygen and some other elements have ordinarily involved the inclusion of such elements as silicon, aluminum or others, which in turn have invariably resulted in a residue of non-metallic inclusions, e.g. as compounds of one or another of the added elements.

Indeed a special feature of the alloy is the complete or virtual absence, in steel of the defined character and purity, of such elements as named above (and of compounds of them); thus in the compositions described below, aluminum is wholly absent, and silicon is present, if at all, as a residue of very low concentration, not more than 0.05% and usually much less. The alloy is also prepared and designed to have up to 1% but preferably not more than a relatively small amount of manganese, say 0.08% to 0.18%, or even essentially zero manganese, limitation to this small amount of manganese being an unusual and advantageous feature, with corresponding avoidance of undesired contamination (e.g. detectable inclusions of non-metallic compounds) that often accompanies or results from a larger quantity of this element.

At the same time, the major or significant nonferrous elements in the composition, e.g. carbon, chromium, nickel and polybdenum, accomplish results or functions which they could not heretofore achieve, including attainment of their functions in a remarkably better way or to a new and higher order of effect, or in an improved manner of coaction, all believed to be made possible, at least to considerable extent, by virtue of the other circumstances of the alloy as explained above.

Columbium, or a substitute for it in some cases, vanadium, is included, chiefly for purposes of grain refinement, but excellent effects of this character are attained with a distinctly lesser order of quantity of the element than has heretofore been deemed necessary for good grain refinement. For instance, whereas prior proposals (for

steels of carbon content as in the present alloys) have been to utilize 0.15% or more columbium, e.g. amounts up to and beyond 0.2%, as affording essentially maximum grain refinement without serious impairment of mechanical properties, the present invention requires a lower range of columbium, viz. 0.03% to 0.10%, to get similar or even better refinement of grain, while achieving superior mechanical properties. This difference is thought to be achieved by virtue of the exceptional cleanliness of the present alloys.

The following Table I represents the overall ranges of ingredients, including alloying ingredients (i.e. the effective or required elements in addition to iron), and also the absence or near-absence of residue or other unwanted ingredients, that characterize the compositions of the invention. It may be noted that in a limited, low range manganese can be deemed an alloying ingredient, although it is conceived that very useful products may be made without manganese. In this table, the values represent approximate percentages, by weight, of the total alloy except in the case of oxygen, nitrogen and hydrogen, expressed as parts per million (p.p.m.) by weight. The table thus defines the limits in content of the several elements (with the remainder iron) as now understood to be requisite, in broad respects, for realization of basic advantages of the invention.

Table I

	C	Cr	Ni	Mo	Mn	Cb	Si	P	S	O <sub>2</sub>	H <sub>2</sub>	N <sub>2</sub>
Min.....	0.15	1.40	2.0	0.60	nil	.03	nil	nil	nil	nil	nil	nil
Max.....	0.60	1.80	4.0	1.20	1.0	.10	0.05	.01	.01	.20	.15	.40

<sup>1</sup> Parts per million.

An unusual advantage of the defined steel in the carbon range up to about 0.35% (the preferred range being 0.20 to 0.30%) is weldability after heat treatment. This is very important in building large structures, such as welded ship hulls, notably submarine hulls, docks, large machine construction, and the like, which cannot be heat treated after completion. Hence in a specific sense the invention resides in alloys as prescribed in Table I, but limited to a carbon range of 0.15% to 0.35%, approximately. In the upper range of carbon, from above about 0.35% to about 0.60%, many advantages of the steel can still be realized, including a high order of toughness, and unusual resistance to the effects of sharp notches and the like under high degrees of stress, even though the heating effects of welding may be so adverse as not to permit such operation on the fully heat treated metal; instances of utility of the alloys in this range are bearings and various other forgings.

The particularly important feature of the alloys in being characterized by essentially complete absence of non-metallic elements, especially oxygen, and being free or essentially free of silicon, will be evident at once from Table I. A further and very significant aspect of improvement, with respect to alloys as defined in Table I, is that deoxidation has been effected without the employment of elements such as silicon or aluminum.

In some cases, for grain refinement, vanadium can be substituted for columbium if desired. The required quantity of vanadium, for the same effect, is about twice that of columbium, e.g. an outside range of about 0.06% to 0.20%. Expressed in another way, to the extent that vanadium is used in selecting a metal from the grain-refining group consisting of columbium and vanadium, the use of vanadium may be considered as replacing columbium and to the extent that vanadium thus in part or wholly replaces columbium, the amount of vanadium can be chosen to be approximately twice the amount of columbium replaced.

A particularly significant characteristic of the alloys in presently preferred embodiments is essentially complete

freedom from inclusions, i.e. non-metallic inclusions. As representative of results which are usually equalled or surpassed in this respect, with the present alloys, the following table of inclusion ratings is given, being optical determinations of small polished specimens made according to the Jernkontoret (JK) Chart, A.S.T.M. Designation E45-60T:

Table II

A		B		C		D	
T	H	T	H	T	H	T	H
0	0	0.5	0	0.5	0	1.0	0.5

It will be understood that A, B and C refer respectively to sulfide, alumina and silica type inclusions, D to globular type oxides, and T and H respectively to the so-called thin and heavy series of appearance of the inclusions. The values correspond to the scale of approximate concentrations or counts given on the chart, half-values being interpolated.

The individual and cooperative functions of the alloying ingredients are best expressed by the fact that the desired high strength and high toughness are attained

(especially for plate and similar applications), after heat treatment. Individually, chromium contributes hardening to the metal and cooperates with the nickel in affording superior mechanical properties, and also affords increased strength at elevated temperatures, in coaction with molybdenum. Nickel serves a highly significant toughening function and promotes other advantageous characteristics, including facility in heat treatment, while molybdenum likewise contributes to the strength of the composition, especially at high temperatures, and inhibits embrittlement which might occur as the result of tempering or similar treatment. When used, manganese also cooperates in the desired results, as in promoting hardenability. Columbium has significant advantages for high strength alloys, excellent grain refinement being attained in the present invention with an unexpectedly low content of this element.

With respect to the ranges of ingredients in Table I, some aspects of the significance of these ranges are as follows: chromium in amount above about 1.80% appears to cause embrittlement of the alloy, while decrease of the chromium below about 1.40% results in reduction in the hardenability of the composition. Reduced hardenability also appears when the nickel content is less than approximately 2.0%, and even more significantly, the toughness is then reduced. In the case of this relatively expensive alloying element, the stated maximum of about 4.0% is primarily an economic limit, essentially no advantage being achieved, in most cases, with higher proportions.

As to molybdenum, alloys having less than about 0.60% of this ingredient exhibit reduced strength properties when tempered in accordance with conditions of temperature understood to be suitable for the alloy. In compositions containing more than about 1.20% molybdenum the austenitizing temperature must be raised. This element is somewhat costly, and the upper limit is thus, as in the case of nickel, somewhat governed by economic considerations.

A significant effect of manganese, however, is that it serves to tie up sulfur in steel; the resulting manganese sulfides have a high melting point, and the action of manganese thus prevents the formation of undesirable ferrous sulfides. If not thus avoided, the latter compounds, having low melting points, and collecting in the grain boundaries, tend to melt during hot working, so as to produce so-called hot shortness. In the present alloys, the sulfur content is very low, so that a limited amount of manganese, usually up to about 0.18%, suffices to account for the sulfur although it is permissible to use amounts up to about 1% to promote other desirable properties. The resulting small quantity of manganese sulfide appears to be soluble, i.e. to be dissolved in the alloy. Hence it does not form contaminating inclusions; indeed essentially none such are found on examination, as shown by Table II above.

Thus as used, manganese keeps the steel from becoming hot short, but manganese in substantially greater amount (combining with more sulfur), would tend to form precipitated inclusions, and also to promote the erosion of pouring refractories, entraining additional non-metallic particles in the metal. Furthermore, because of its relatively low vapor pressure, manganese in larger quantities may be vaporized and lost, in part, during presently preferred processes of preparing the alloys, with consequent difficulty in controlling the analysis.

Columbium is a very expensive ingredient and the advantages of using it in relatively small amounts, as achieved with the present invention, are correspondingly important. It is included primarily to promote grain refinement as in accordance with A.S.T.M. Specification E19-46. Grain refinement data for the present alloys have been obtained at 925° C. after 8 hours of carburizing, and show that the degree of grain refinement obtainable with this element can be reached in the present alloys with substantially lower amounts of the element than as prescribed in prior practice. Below about 0.03%, columbium shows no substantial grain refinement, while over 0.10% further addition is at least wasteful in accomplishing no further function; indeed the present understanding is that increase of the content of columbium beyond this limit may start to reverse the operation and coarsen the grain size.

Silicon in the alloy is simply a residual, there being no deliberate addition. As explained further below, the alloys are prepared in such way that silicon is kept as close to zero as possible. In past known practice of conventional operation, it has not been feasible to reach this low a content of silicon, at least unless undesirably high quantities of oxygen have been allowed to remain or unless other undesirable conditions or additions have been permitted. In amounts appreciably above about 0.05% silicon tends to form various reaction products which are retained as silicate or silica inclusions.

Very low contents of phosphorus and sulfur are indicated, as these elements are undesirable. Sulfur, for example, interferes with weldability and also reacts with other elements to form non-metallic inclusions. Phosphorus, in significant amounts, has an embrittling effect on the alloy.

Oxygen is particularly undesirable, especially in that it tends to react with various other elements to form oxides which also remain as non-metallic inclusions. The defined, extremely low content of oxygen represents a particularly significant feature of the alloy, under the circumstance of the relative absence of certain other elements, as explained.

Hydrogen is also kept extremely low; with the hydrogen content above 5 p.p.m., there is risk of the formation of difficultly detectable flaws known as "flakes," such being internal hairline stress cracks in bloom and billet stock and heavy section forgings. Nitrogen is also undesirable in general respects, the maintenance of a very low nitro-

gen content being specifically advantageous in affording good ductility.

The preparation of these alloys is effected in a manner to achieve the desired composition and characteristics, especially with respect to cleanliness of the product and avoidance of unwanted elements or contaminations as explained herein. In general, particularly effective procedures include at least one stage of high vacuum melting employing a consumable electrode which has the desired composition of iron and alloying ingredients. The material of the electrode is melted to form an ingot or the like by the passage of electric current which produces an electrical discharge between the electrode and the resulting pool of metal. A further and preferred feature of very special significance is the utilization of carbon, e.g. incorporated in the electrode composition in appropriate excess of amount, for deoxidizing the material during at least one high vacuum step.

Suitable procedures of this sort are described and claimed in the following copending United States patent applications, being here conveniently and respectively identified as processes A, B and C, viz.: application of Sidney W. Poole, Thomas E. Perry and Roderick J. Place, Serial No. 153,650, filed November 20, 1961, for Process for Production of Ultra Clean Steel (Procedure A); application of Thomas E. Perry, Serial No. 194,446, filed May 14, 1962, for Process for Production of Ultra Clean Steel (Procedure B); and application of Thomas E. Perry, Roderick J. Place, John A. Rinebolt and Sidney W. Poole, Serial No. 203,091, filed June 18, 1962 (executed June 14, 1962, and now on file in the U.S. Patent Office) for Process for Production of Exceptionally-Clean Steel (Procedure C). The disclosures of the cited applications, which describe processes especially appropriate for making the present alloys, are believed to be adequately summarized hereinbelow for such purpose, but may nevertheless be deemed to be incorporated herein by reference.

In particular, one effective operation, especially in accordance with the first of the above cited applications (Process A), involves the utilization of iron powder of very high purity, such as electrolytic iron, which is then blended with carbon and desired alloying metals or with powder or powders consisting of one or more alloys of iron with such metals, the resulting mixture being formed or briquetted, as with the aid of pressures of the order of 50,000 pounds per square inch, so as to form consumable electrodes. The consumable electrode is then melted under vacuum by the use of electric current, discharging between the electrode and the rising body or pool of metal melted therefrom in the vacuum vessel (or at the outset a suitable base in such vessel) whereby a cast ingot results.

This ingot is then further refined by repeating the vacuum melting operation, utilizing the ingot as electrode, or an electrode formed from the ingot by forging or by assembly of appropriate pieces derived from the first ingot. In the second vacuum melting step, the mode of electrical heating is similar to the first, so as to yield a final ingot constituting the desired alloy, which can then be converted by rolling or other operations into ultimate stock for use, such as plate, sheet or the like. In the vacuum melting steps, the vessels preferably comprise suitably cooled crucibles of copper or the like so as to avoid danger of refractory contamination.

The high purity iron used as starting material may be such, in accordance with known practices, as to have very low contents of sulfur and phosphorus, and preferably as little oxygen as possible, although it is not ordinarily contemplated that oxygen as low as is required in the present alloys will be characteristic of the purified iron powder. Indeed such iron powder may be expected to have from 0.06% to as much as 0.2% oxygen, far above the low requirements of the present compositions. It will be understood that removal of sulfur, for example, from electrolytic iron, can be satisfactorily effected by high tem-

perature treatment with so-called wet hydrogen, as at 1500° to 1700° F. for 2 to 4 hours.

The briquetting of the electrode material for the first vacuum melting step can involve, as well as pressing, vacuum sintering of the electrode or its sections at about 1750° F., or indeed sintering in an inert gas, such as argon, at temperatures up to 2200° F. Indeed any suitable technique may be employed for making these electrodes, so long as they contain the required materials of appropriate purity and have sufficient strength for the operation whereby the electrode is melted off by the discharge or arc to form the ingot.

In the first vacuum melting step, pressure is maintained at not more than 1 millimeter (1000 microns). In the second vacuum melting step, utilizing an electrode forged or otherwise derived from the product of the first step, a still higher vacuum is used, not more than 100 microns (0.1 mm.) and preferably no more than 10 microns (0.01 mm.), all such definitions of vacuum being expressed as pressure in microns or millimeters of mercury.

A particularly important feature of the vacuum melting operations is the utilization of carbon for removal of oxygen. To this end, excess carbon is included in the electrode of the first step, in amount sufficient to deoxidize by combination of carbon and oxygen to yield carbon monoxide, which passes off and out, under the action of the vacuum pumping instrumentalities. In general, for most cases, the amount of carbon to be employed is roughly equal to the amount of carbon desired in the ultimate alloy (i.e. the so-called carbon aim) plus from 1.35 to 2.0 times the amount of carbon stoichiometrically required for combination with the oxygen content (determined by analysis) in the preliminary alloy composition, this total being reduced by the amount of any carbon already present in the alloy material. Selection within the above range of factors for computing carbon content (and in similar ranges for other processes) can be readily made with test melts, although as a rule the lower end of the range would be chosen for steel of higher carbon content (in the overall range of the present alloys), and vice versa, the higher end of the range also being taken in cases where the melting operation is to be relatively rapid.

The carbon may be added in any suitable, finely divided form of high purity, such as graphite. Experience shows that proportions of carbon of the above order are desirable, the excess carbon, beyond that consumed by reaction with oxygen and beyond that desired to remain in the alloy, being lost in the course of the operations, by mechanisms which are not entirely understood but the extent of which can be accurately predicted, i.e. as is implicit in the above recital of a mode of determining the excess carbon requirement. With carbon included in the amounts described, it is found that the steel is deoxidized in an unusually effective way, such reaction occurring chiefly or indeed essentially wholly in the first vacuum melting step, the second step functioning for further refinement and also to eliminate product gases and provide a melt free of holes or pores.

In some cases, it is found that a single vacuum melting operation is sufficient, both to remove the oxygen by carbon deoxidation and to yield a highly pure, non-gassy ingot. In such case, the single melting step should be performed with relatively high vacuum, i.e. pressure below 100 microns, such operation being attainable in this single step, providing the nature of the electrode material or other conditions are such that the gas emanation is limited or the vacuum maintenance is otherwise correspondingly effective to maintain the requisite low pressure. This process is described in the second of the above-mentioned applications (Process B).

Another preferred procedure is as set forth in the third of the above applications (Process C), and involves a first melting stage, which may be characterized as an air-melting step, in a suitable furnace of conventional

sort (very preferably an electric, i.e. electric-arc furnace), operated under ordinary rather than vacuum conditions and utilizing conventional charge material, including steel scrap (if desired), the composition of the charge being of course determined and adjusted so as to achieve the desired ultimate alloy analysis, taking into account the purifying operations that occur in this first furnace stage. This step, yielding an open or non-killed steel, for example, whether as performed in electric arc, open-hearth, pneumatic, e.g. Linz-Donawitz process, or induction melting, is conducted in accordance with normal practice for the operation of such furnaces or melting procedures, except that when the melt is tapped, the melt is essentially free of strong metallic deoxidizers. As indicated, an electric furnace is at present preferred because of available large capacities and because of the capability of maintaining a deoxidizing type of slag and thus a flexibility of composition; such furnace also affords a particularly good control of sulfur in the melt.

A presently preferred mode of carrying out the operation in the electric furnace is to start with an oxidizing slag, utilized in a known manner; the initial melting, by use of electric arc from appropriate electrodes extending to the charge, is thus effected under an oxidizing slag of such type. At the same time (after the charge is melted), the melt is blown with highly concentrated dry oxygen gas using a suitable lance to introduce oxygen below the surface of the metal, or alternatively an iron oxide or other suitable composition preferably low in manganese may be added. The oxygen addition is of the nature of decarburization, reducing the carbon, and promotes the development of high temperature, and uniformity of temperature, and likewise the elimination of metallic deoxidizers such as aluminum and silicon. The oxygen addition also serves to reduce the hydrogen content in the metal.

At an intermediate stage in the electric arc furnace melting, the first slag is run off and replaced with a finishing slag of a reducing type, viz. a calcium carbide type of known character. Under such slags, sulfur can be reduced to low levels and, in the absence of silicon and only a low manganese residual, the carbon and oxygen contents can approach equilibrium at the desired carbon aim for the electric furnace heat.

The carbon aim for the electric furnace heat produced by the carbon deoxidation practice is several percentage points (i.e. hundredths of one percent) higher than the final carbon aim desired in the product resulting from the subsequent vacuum consumable electrode melt (which is a following stage in the process). This is done to allow for the carbon drop experienced during vacuum remelting of carbon deoxidized electrode ingots. In the event that the electric furnace heat does not result in the carbon aim desired certain adjustments can be made in the ladle to achieve precisely the carbon aim desired. Usually, however, carbon losses and carbon utilization can be quite accurately predicted and controlled by anyone skilled in the art so that the carbon content of the melt will meet the carbon aim within close limits. For example, the oxygen content of the ingot metal as used in the subsequent vacuum consumable electrode melt can usually be kept to not more than 0.005% and it is found that for carbon deoxidation in such melt, the carbon adjustment (as in the ladle from the electric furnace) need only suffice to exceed the carbon aim by an amount of 0.02% to 0.03% or thereabout (of carbon in the steel), i.e. the few percentage points mentioned above. Thus if the carbon aim is 0.23%, the electric furnace ingot should ordinarily contain 0.25–0.26% carbon. In another sense, the amount of carbon to be reached, by addition or other adjustment, in the steel from the electric furnace, is generally the carbon aim plus 1 to 1.5 times the stoichiometric amount required to reduce the oxygen present to carbon monoxide.

The molten metal is tapped from the electric arc furnace and poured into suitable ingot molds, the ingots being utilized as such, or by suitable shaping or assembly, to constitute the consumable electrode of the vacuum melt. Since there is no residual silicon in the molten metal and very little manganese, the steel may be poured as an open steel, into ingot molds without hot tops, and gas evolution may be continued during solidification in the ingot. It is at present deemed preferable, and indeed particularly desirable in order to avoid more than one stage of vacuum melting, that the gas content of the metal be reduced as much as possible. One effective way of accomplishing this operation is by so-called vacuum degassing or vacuum lift degassing, or especially by so-called vacuum ladle degassing, e.g. as described on pages 368, 370 and 369 respectively of the Handbook entitled "Republic Alloy Steels," published by Republic Steel Corporation, Cleveland, Ohio, Copyright 1961. Another reference for vacuum lift degassing is U.S. Patent No. 3,033,550, granted May 8, 1962, to Fritz Harders.

The metal produced from the electric furnace operation, preferably with such degassing, is then utilized for the second melting stage, being a vacuum melting step with the metal supplied as a consumable electrode. Operations are as described above for such vacuum melting, the pressure being kept below 100 microns and preferably not higher than 10 microns. In this stage, further or effective carbon deoxidation occurs, whereby a highly purified ingot is achieved, having unusually low oxygen content and yet remarkably free, as is likewise the case of the other processes defined above, of non-metallic inclusions. Alternatively, the product of the electric arc furnace may be subjected to a two-stage vacuum melting sequence, similar to the first above-mentioned process, except that the consumable electrode in the first stage is prepared from the electric furnace product rather than by the use of high purity iron.

It is believed that the foregoing descriptions of the several methods will serve as sufficient example of the practice of such procedures for making the alloys of the present invention, in that the operations as thus described are followed in each case with appropriate charge material or initial compounding, as to iron, carbon and alloying ingredients, to provide the compositions herein set forth. Specific instances of such compositions set forth hereinbelow, will therefore constitute examples of the preparation of the final alloy in ingot or like form, utilizing one or another of the foregoing operations, as may be identified by reference to the processes (herein called A, B and C) of the separate patent applications above listed.

As generally indicated above, the low alloy, low silicon, high strength steels constituted by the alloys of the present invention afford the advantages of a high strength structural steel, e.g. in the range of 100,000 to 175,000 p.s.i. yield strength, with ductilities greater than and notch sensitivities less than current structural steels. The properties of high ductility and low notch sensitivity, both at normal and room temperatures and at elevated temperatures are equal to or superior to the corresponding properties of structural steels such as currently available, which have strength levels generally less than those of the present alloys. Moreover, in the range below room temperature to about  $-120^{\circ}$  F. the steels herein disclosed are superior to current structural steels; for instance, tested specimens have generally (and advantageously) been found to possess a ductile-brittle transition point, as measured by Charpy Impact Testing and as rated in accordance with U.S. Naval Research Laboratory Drop Weight and Explosive Bulge Tests, of lower than  $-40^{\circ}$  F.

Furthermore, the alloys of this invention exhibit very little or no directionality, i.e. have essentially nil anisotropy, that is to say, little or no variation of mechanical properties with respect to direction of test for such properties when taken in reference to the direction in which

the steel has been worked. It is believed that this highly desirable characteristic is a direct result of the very low content of non-metallic inclusions, and possibly because of a lower trace element content as attained preferably by melting practice of the sort described above.

The ranges or characteristics of temper embrittlement in the present alloys appear to be distinctive. Ordinary structural steels usually have a so-called temper brittle range at about  $500^{\circ}$  to  $700^{\circ}$  F., in that steel tempered at one or another point in this range exhibits a minimum impact resistance (the embrittlement also being noted in tensile tests), as compared with the effect of such treatment at other temperatures (above and below), is being understood that in general such resistance rises as the tempering is effected at temperatures successively higher. In the steels of the present invention, the curve which relates temperature to impact resistance appears to be smoothed out in the lower temperature range mentioned above, but to exhibit a dip in the vicinity of  $950^{\circ}$  F. or so; the relative temper embrittlement there noted, however, does not appear to be as severe as in ordinary structural steel, and is detected only through Charpy impact testing. Hence for at least some purposes, the present alloys can be tempered at a variety of temperatures (even in the last-mentioned range); in general, however, and as presently preferred for optimum results, tempering is recommended at higher temperatures, such as  $1000^{\circ}$  F. and above (e.g.  $1050^{\circ}$  to  $1075^{\circ}$ ), where the toughness of the product is very high.

The foregoing improved characteristics, especially in mechanical properties of the described steels have been determined by standard tests and techniques such as described in the American Society of Metals Handbook (1948), page 88, and A.S.T.M. Specification E8-57T. Specifically, such tests from which results of representative heats are tabulated hereinbelow, provide data as to the tensile yield strength at 0.2% offset, tensile ultimate strength, elongation in a gauge length equal to four diameters of the reduced section of the specimen, and ductility as indicated by the reduction of cross-sectional area of the reduced section of the specimen at the point of failure in test. Charpy V-notch impact tests were performed using a standard specimen as prescribed in A.S.T.M. Specification E23-56T, Type A, these impact tests being understood to provide data as to the energy absorbed by the specimen, necessary to cause fracture under beam-type loading.

The ductile-brittle transition value is that temperature at which the mode of fracture of a specimen changes from a ductile or fibrous mode to a brittle or cleavage (conchoidal or flat surface) mode of failure, the latter being considered a failure of nil ductility. Specifically, the ductile-brittle transition point is that temperature at which the failure is judged to be 50% fibrous.

Not only are the presently improved steels of great utility for general structural uses, but they are of extraordinary advantage in construction of heavy duty equipment such as may be subjected to extremes in temperature and frequent impact loading. An important desideratum of such equipment is that it must have a high degree of reliability, and often that it must have a high strength to weight ratio; in the latter instances the amount of steel used must be kept to a minimum, to the point of precluding additional weight or massiveness of the structural members which is often utilized as a safety factor. Examples of structures employed in unusual conditions of this sort are portable bridges, building trusses, docks, large cranes, other similar construction, and shipbuilding plate. Maintenance of mechanical properties at high levels over a broad range of temperatures is especially necessary where equipment is to be utilized in various climates, e.g. natural conditions varying from  $+100^{\circ}$  to  $-120^{\circ}$  F. Other special uses of the new alloys, particularly for fabricating from heat treated plate, sheet or the like, are in buildings for unusual industrial or military

requirements, construction of missiles (notably large diameter cases for solid fuel rocket motors), and submarine hull plate material.

As has been indicated, attainment of these results, particularly high strength and high toughness, the latter being indicated by exceptionally high impact properties, and the occurrence of these properties throughout a useful range of temperatures and their existence and maintenance without substantial deterioration in the course of practices incidental to final fabrication as hereinabove described (very importantly, including welding in the case of steel of the carbon range up to 0.35%, e.g. plate and forgings of such metal), and likewise the reliability of attainment of these properties and their uniformity in the composition (with corresponding uniformity of strength-to-weight ratio), are believed to be occasioned by the precise composition of the steel, not only as to intended ingredients but particularly as to the absence or low levels of various elements of which one or more have been conventionally unavoidable in prior compositions appropriate for commercial manufacture and sale. The invention further extends, as will be appreciated, to the method of producing alloys and to the method of producing steel stock such as plate, sheet and the like, especially in that these specific, new high strength alloys are produced, and are indeed enabled to be produced with the specified chemical compositions, by following one or another of the stated melting and deoxidizing practices.

Expressed in another sense, the cleanliness of the alloys, the essential absence of non-metallic inclusions and the very low interstitial gas content, are believed to coact effectively in producing the improved properties. A special feature is the complete or almost complete avoidance of silicon, heretofore generally relied upon for deoxidation, i.e. for so-called silicon-killed steels. When used in steel in amounts suitable for the deoxidizing function, leaving a necessary residue of about 0.15% Si or more after killing, silicon inevitably tends to produce non-metallic inclusions, such as silica or silicates; these are extremely sharp, friable inclusions that represent internal notches or flaws in the metal and reduce its mechanical properties, including its toughness or resistance to impact, and also tend, depending on size and orientation, to contribute to anisotropy. The very low value of sulfur content is also effective in minimizing anisotropy. In the present alloys, silicon is kept no higher than about 0.05%, and indeed usually at 0.02% or less, so that there is no appreciable effect of the sort just described.

In the removal of oxygen by carbon deoxidation during the described melting operations for the present alloys, the oxygen escapes as the gaseous product carbon monoxide, thus avoiding appreciable interstitial gas content and avoiding, as indicated, solid insoluble oxide reaction

No aluminum is included at all. In conventional practice if aluminum is employed as a deoxidizer, there is likewise the invariable result of non-metallic inclusions in the steel, being hard, abrasive particles of aluminum oxide. Aluminum, moreover, acts preferentially, relative to carbon, in combining with oxygen in steel. Even in ordinary melting of alloys by induction or electric arc furnace, where silicon (or aluminum or manganese) is used for killing the steel, conventional practice still leaves a residual oxygen level in the metal of the order of 50 to 60 p.p.m., as contrasted with the maximum of about 20 p.p.m. in the present alloys, preferred compositions being even lower, i.e. 10 p.p.m. and below.

It is prior experience, too, that if no silicon or metallic deoxidizer is used, as in so-called rimming steel, the ingot is very porous or open because the carbon-oxygen reaction continues as the steel solidifies in the mold, trapping minute gas bubbles. Such metal would be poor for structural steel as it would lack reliability in mechanical properties. In the manufacture of the alloys of this invention, oxygen is removed before the metal solidifies, and a sound, solid, fully deoxidized ingot is always achieved.

While endeavor has been made above to explain the unusual properties and uniformity of the improved steel, including its superior notch toughness, as due to various stated factors, it will be appreciated that these explanations are deduced from experimental and comparative tests and that the utility and advantages of the invention are in no event dependent on any particular scientific theory. In the realm of theory and likewise without limitation, it is further noted that the combination of low non-metallic inclusions and low gas content may perhaps indicate that there is less lattice distortion due to interstitial atoms in the unit cell, thereby affording a structure which more closely approaches the theoretical and mechanical impact and toughness capabilities of the alloy. The significant fact, however, is that the described practical advantages have been well demonstrated, regardless of their cause.

Another beneficial effect in articles made of the improved steel resides in superior welding properties; operations such as tungsten inert gas arc welding and metallic inert gas arc welding are believed to be aided by the highly clean nature and lower impurity content of the metal.

For optimum realization of the advantages of these alloys, it is at present believed that the composition should be kept within the preferred ranges approximately expressed in the following Table III (values being percentages by weight except where expressed as parts per million by weight):

Table III

	C	Cr	Ni	Mo	Mn	Si	Cb	P	S	O <sub>2</sub>	H <sub>2</sub>	N <sub>2</sub>
Min.....	0.20	1.50	2.65	0.80	nil	nil	.04	nil	nil	nil	nil	nil
Max.....	0.30	1.70	3.25	1.00	0.18	.02	.09	.01	.008	.15	.2	.130

<sup>1</sup> Parts per million.

products such as occur when silicon or other elements, such as aluminum and manganese, are utilized for deoxidizing action. In the present compositions manganese is likewise usually maintained sufficiently low in amount so that no trouble is caused by formation of its compounds; indeed optionally (if this element is not otherwise needed) it may be omitted entirely should correspondingly extreme cleanliness be required in this respect, such omission being most readily accomplished by melting procedure of the first type (above) utilizing high purity electrolytic iron.

The balance of the alloy in all instances is iron. The carbon content of about 0.20% to about 0.30% is at present preferred, both as above and within the otherwise broader ranges of Table I. Preferably also, manganese is included only in such amount (often only 0.08 to 0.12%) as will take up the sulfur present, without forming an appreciable quantity of detectable inclusions, i.e. sulfide particles. Analysis may sometimes show aluminum in extremely low values, e.g. below 0.01%, but such can be deemed an essentially nil content in view of the nature of this element.

By way of more specific description of specimen alloys that have been produced and tested in accordance with the invention, such compositions have involved 0.10 to 0.15% manganese, 1.40 to 1.65% chromium, 2.75 to 3.25% nickel, 0.80 to 1.0% molybdenum, 0.03 to 0.07% columbium, not more than 0.05% silicon, no aluminum and extremely low contents of phosphorus, sulfur, oxygen, hydrogen and nitrogen, the latter being at or well below the maxima indicated in Table I hereinabove, and mostly within the ranges of Table III. One series of such alloys was made with a carbon content of 0.28 to 0.32%. These products, after suitable heat treatment, including quenching, and tempering at a point appropriate for desired results (for the most part, and preferably, upwards of 1000° F.), yielded good properties of strength and toughness. Alloys were also prepared, having the above analysis with carbon in the range of 0.23 to 0.28%. These showed 0.2% offset yield strength of well above 150,000 p.s.i., tensile strength of the order of 170,000 p.s.i., ductility as represented by 70% (average) reduction in area, and elongation in a four diameter length of about 17.5% average. In these tests, the alloy was worked to the form of a 1 inch thick plate which was heat treated and then tempered at 1050° F. Test specimens employed were round threaded end tensile bars with 0.252 inch gauge diameter, machined from such plate. Charpy V-notch impact tests, i.e. on a V-notched bar, showed energy absorption, in foot pounds, of 82 at room temperature, 80 at 0° F., 76 at -40° F., 57 at -120° F., 37 at -160° F. and 22 at -200° F.

As explained, the complete procedure of making steel for use, in accordance with the invention, advantageously involves heat treatment (usually after any considerable forming operations for fabrication) for purposes of attaining hardness and the desired mechanical properties. In general, appropriate heat treatment for these steps of the process, includes normalizing (usually after forging and preferably also after hot rolling) and particularly (in most cases) austenitizing followed by quenching in water or oil, and finally (as equally essential in most cases) tempering at a suitable temperature followed by cooling in air at room temperature. The temperature reached in austenitizing, i.e. in the metal to be quenched, is ordinarily in the range of about 1500° F. and above, it being appreciated that at very high temperatures (e.g. 1800°) the operation may have some unwanted effects

ness. As a rule, the very highest strength is retained with tempering at a lower range, but greatest toughness at the higher temperature of tempering. Thus the choice of operations in heat treatment depends on conventional principles: for example, normalizing may be omitted if its effects are not needed; or if extreme toughness at the expense of strength should be required for some limited, special use, it is conceived that the treatments might be only normalizing and tempering.

For instance, to serve many uses, a specifically desirable sequence of operations of heat treatment for the present alloys, following the rolling of the ingot into plate or sheet (and forming, if desired), is:

(a) Normalizing at a temperature of 1700° to 1800° F., e.g. for one hour per inch of thickness of the plate; the steel being then cooled in air to room temperature;

(b) Austenitizing at 1500° to 1650° F. (no higher being needed in most cases), and then quenching in water or oil to room temperature, higher carbon content alloys being quenched in oil and lower carbon compositions in water; and

(c) Tempering at a selected temperature, preferably above about 1000° F., with subsequent cooling in air to room temperature.

Four specific examples of particular alloys produced in accordance with the invention are represented by Table IV, below. These are specifically designated as Heats Nos. 309, 493, 528 and 515. More particularly each of Heats Nos. 309 and 493 was prepared by procedure starting with high purity electrolytic iron powder and utilizing two successive consumable electrode vacuum melting stages as specifically described above for Process A. Heats Nos. 528 and 515 were prepared by the process designated above as C, starting with electric furnace melting under conditions as defined and then followed by consumable electrode vacuum remelting. In these instances, a degassing operation intermediate the furnace melt and the vacuum operations was not employed, and in consequence, two stages of consumable electrode vacuum melting were utilized, in accordance with such stages as described for Process A. In all of the operations carbon deoxidation was effected during vacuum melting, utilizing excess carbon in proportion and manner as explained hereinabove.

The following are the chemical analyses of the described four heats (balance iron):

Table IV

Heat	Percent										P.p.m.		
	C	Mn	S	P	Si	Ni	Cr	Mo	Cb	Al	O <sub>2</sub>	H <sub>2</sub>	N <sub>2</sub>
309	.25	.01	.006	.005	.02	2.7	1.5	.9	.04	.003	6	.5	20
493	.23	.16	.006	.005	.02	3.05	1.55	.95	.09	.001	3	1	5
528	.20	.18	.005	.008	.02	3.15	1.62	.90	.04	.002	10	.5	5
515	.26	.17	.005	.009	.02	3.08	1.7	.94	.04	.008	-----	-----	-----

in scaling, warpage or the like. Desirably the higher tempering temperatures, e.g. on the order of 1000° F. or above, are employed, although such temperature may be selected depending on the strength and other properties desired and on the chemistry of the alloy, in accordance with well known practices in the art.

As will be understood, the quench (after heating to put carbon into solution) usually serves to develop martensite in the steel, affording strength and hardness but with a tendency to brittleness, and tempering then imparts tough-

In each case the resulting ingot (or ingots) was reduced by rolling to plate form and the plate was subjected to heat treatment, including normalizing at 1750° F., cooling at room temperature, austenitizing at 1650° F., quenching in water, and thereafter tempering. Various tempering temperatures were utilized, the following Table V setting forth the results achieved with various specimens of the several alloys, respectively so tempered; the table is believed to demonstrate, in itself, the exceptional properties attained.

Table V

[Yield point and max. stress, tensile, given in thousands of lbs.; 000 omitted]

Heat	Temper Temp., ° F.	Yield Point, 0.2% Offset	Max. Stress	Elong., percent (4 diam.)	Percent Reduct. Area	Impact (ft.-lbs.) Charpy-V		
						At Room Temp.	At -108° F.	At -120° F.
309	1,200	110	124	22	74	140	-----	99
	1,100	134	148	19	71	107	-----	67
	1,050	158	171	18	70	82	-----	37
	800	177	190	14	60	55	-----	24
493	800	174	194	14	55	40	-----	-----
	1,100	132	150	18	64	91	-----	-----
528	1,000	163	182.5	16	65	60	-----	-----
	1,050	142	158	19	72	105	89	-----
515	400	200	214	14	54	-----	-----	-----
	1,000	177	193	17	74	-----	-----	-----

In this table the impact results are for Charpy V-notch tests at temperatures as indicated, the values (by convention) being given as energy absorption in foot pounds, e.g. energy for breaking the test bar.

As further characterizing these examples of the invention, the following Table VI shows the non-metallic inclusion ratings and gas contents of certain of the same heats. In this table the inclusion ratings were made by using the Jernkontoret (JK) Chart (A.S.T.M. Designation E45-60T) and the gas content values were determined by the vacuum-fusion analysis technique.

Table VI

Heat	A		B		C		D		P.p.m.		
	T	H	T	H	T	H	T	H	O <sub>2</sub>	H <sub>2</sub>	N <sub>2</sub>
309	0	0	1.0	0	0.5	0	1.0	0	6	0.5	20
493	0	0	0	0	0	0	0.5	0	3	1	5
528	0	0	0	0	0	0	1.0	0.5	10	0.5	5

As will be appreciated, all of the values in this Table VI represent an extremely low content of undesirable inclusions as well as of the several gases.

Generally stated, the invention readily permits accomplishment of the specific objects set forth at the outset hereinabove, respecting ranges of yield strength (0.2% offset), tensile strength (max. stress), and ductility, as well as other factors of toughness, weldability and the like. The expressed upper limits of strength, or higher values, have been readily achieved in desired cases; indeed the attainment of values (similarly measured) of yield strength in the range of at least about 140,000 p.s.i. or higher, and tensile strength in the range of at least about 155,000 p.s.i. or higher, can be taken to represent specially significant advantage for the preferred practice of the invention, in steel of this character. Of course, as already indicated, values of one or more factors even below the broader-stated ranges can sometimes be tolerated while taking advantage of new results in other respects, a further instance being special situations where relatively lower ductility may be allowed.

It is to be understood that the invention is not limited to the specific compositions and operations herein described by way of example but can be carried out in other ways without departure from its spirit.

We claim:

1. A steel alloy consisting essentially of about: 0.15% to 0.60% carbon, 1.40% to 1.80% chromium, 2.0% to 4.0% nickel, 0.60% to 1.20% molybdenum, metal selected from the group consisting of columbium and vanadium, in an amount of from 0.03% to 0.10% columbium when the selected metal is columbium alone, and with vanadium in approximately twice the amount of replaced columbium to the extent that vanadium replaces columbium in the selected metal, nil to 1.0% manganese, and quantities ranging from nil to not more

than the following amounts of the following impurities, 0.05% silicon, 0.01% phosphorus, 0.01% sulfur, 20 p.p.m. oxygen, 5 p.p.m. hydrogen and 40 p.p.m. nitrogen, and the balance iron.

2. A steel alloy consisting essentially of about: 0.15% to 0.35% carbon, 1.40% to 1.80% chromium, 2.0% to 4.0% nickel, 0.60% to 1.20% molybdenum, metal selected from the group consisting of columbium and vanadium, in an amount of from 0.03% to 0.10% columbium when the selected metal is columbium alone and with vanadium in approximately twice the amount

of replaced columbium to the extent that vanadium replaces columbium in the selected metal, nil to 0.18% manganese, and quantities ranging from nil to not more than the following amounts of the following impurities, 0.05% silicon, 0.01% phosphorus, 0.01% sulfur, 20 p.p.m. oxygen, 5 p.p.m. hydrogen and 40 p.p.m. nitrogen, and the balance iron; said alloy being essentially free of non-metallic inclusions: and said alloy being capable of providing a steel article which after heat treatment has a yield strength of at least 140,000 p.s.i. and tensile strength of at least 155,000 p.s.i., and is capable of being welded in such heat treated condition while substantially retaining the aforesaid properties.

3. A heat treated steel article made of steel alloy consisting essentially of about: 0.15% to 0.60% carbon, 1.40% to 1.80% chromium, 2.0% to 4.0% nickel, 0.60% to 1.20% molybdenum, metal selected from the group consisting of columbium and vanadium, in an amount of from 0.03% to 0.10% columbium when the selected metal is columbium alone and with vanadium in approximately twice the amount of replaced columbium to the extent that vanadium replaces columbium in the selected metal, nil to 1.0% manganese, and quantities ranging from nil to not more than the following amounts of the following impurities, 0.05% silicon, 0.01% phosphorus, 0.01% sulfur, 20 p.p.m. oxygen, 5 p.p.m. hydrogen and 40 p.p.m. nitrogen, and the balance iron; said alloy being essentially free of non-metallic inclusions; and said heat treated article having a yield strength of at least 100,000 p.s.i. and tensile strength of at least 115,000 p.s.i.

4. A steel alloy which is low in non-metallic inclusions and which consists essentially of about: 0.15% to 0.35% carbon, 1.40% to 1.80% chromium, 2.0% to 4.0% nickel, 0.60% to 1.20% molybdenum, metal selected from the group consisting of columbium and vanadium,

in an amount of from 0.03% to 0.10% columbium when the selected metal is columbium alone and with vanadium in approximately twice the amount of replaced columbium to the extent that vanadium replaces columbium in the selected metal, nil to 0.18% manganese, and quantities ranging from nil to not more than the following amounts of the following impurities, 0.05% silicon, 0.01% phosphorus, 0.01% sulfur, 20 p.p.m. oxygen, 5 p.p.m. hydrogen and 40 p.p.m. nitrogen, and the balance iron; said alloy being capable of providing a steel article of high strength and toughness after heat treatment which comprises heating in the range of 1500° F. and above, quenching and tempering in the range of 1000° F. and above.

5. A steel alloy consisting essentially of about: 0.20% to 0.30% carbon, 1.50% to 1.70% chromium, 2.65% to 3.25% nickel, 0.80% to 1.0% molybdenum, metal selected from the group consisting of columbium and vanadium, in an amount of from 0.04% to 0.09% columbium when the selected metal is columbium alone and with vanadium in approximately twice the amount of replaced columbium to the extent that vanadium replaces columbium in the selected metal, nil to 0.18% manganese, and quantities ranging from nil to not more than the following amounts of the following impurities, 0.02% silicon, 0.01% phosphorus, 0.008% sulfur, 15 p.p.m. oxygen, 2 p.p.m. hydrogen and 30 p.p.m. nitrogen, and the balance iron.

6. A heat treated steel article made of the alloy defined in claim 5, which has a yield strength of at least 140,000 p.s.i. and tensile strength of at least 155,000 p.s.i.

7. A steel article as defined in claim 6, which has been tempered in the range of 1000° F. and above, which is essentially free of non-metallic inclusions and which is capable of being welded while substantially retaining the aforesaid properties.

8. A heat treated steel article made of the alloy defined in claim 1, which has a carbon content from about 0.20% to 0.30%, and which has a yield strength of at least about 175,000 p.s.i. and tensile strength of at least 155,000 p.s.i.

9. A process of making a steel article having high strength and high toughness, comprising: preparing, by melting into ingot form, an alloy consisting essentially of about: 0.15% to 0.60% carbon, 1.40% to 1.80% chromium, 2.0% to 4.0% nickel, 0.60% to 1.20% molybdenum, metal selected from the group consisting of columbium and vanadium, in an amount of from 0.03% to 0.10% columbium when the selected metal is columbium alone, and with vanadium in approximately twice the amount of replaced columbium to the extent that vanadium replaces columbium in the selected metal, nil to 1.0% manganese, and quantities ranging from nil to not more than the following amounts of the following impurities, 0.05% silicon, 0.01% phosphorus, 0.01% sulfur, 20 p.p.m. oxygen, 5 p.p.m. hydrogen and 40 p.p.m. nitrogen, and the balance iron; said preparation including the step of melting an electrode which comprises the aforesaid ingredients, into an ingot form, by passage of electric current, under a vacuum constituting a pressure of not more than 100 microns, so as to yield an ingot having the aforesaid composition; converting metal of said ingot into the form of said article; and subjecting said metal in the form of said article to heat treatment to produce said article having high strength and high toughness.

10. A process as defined in claim 9, in which in the recited melting step the electrode includes additional carbon to remove excess oxygen, said carbon reacting to remove said oxygen during said melting by passage of electric discharge, and in which the heat treatment comprises heating in the range of 1500° F. and above, quenching and tempering in the range of 1000° F. and above.

11. A process as defined in claim 10, in which the alloy is prepared and melted to contain about 0.15% to

about 0.35% carbon, and in which the said heating is effected in the range of 1500° to 1650° F. and is preceded by a step of normalizing the article by prolonged heating in the range of 1700° to 1800° F. and cooling slowly to room temperature.

12. A process as defined in claim 11, in which the alloy is prepared and melted to contain about 0.20% to about 0.30% carbon.

13. A process of making a steel article having high strength, comprising: preparing, by melting into ingot form, an alloy having the composition defined in claim 1; converting metal of said ingot into the steel article by deforming operation, and subjecting the article to heat treatment comprising heating at a temperature in the range of 1500° F. and above, quenching, and tempering.

14. A process as defined in claim 13, in which the alloy is prepared to contain carbon in an amount not more than about 0.35%, and in which the heat treatment includes tempering in the range of 1000° F. and above, said alloy being prepared and said heat treatment effected to produce a steel article having high toughness and ability to be welded while substantially retaining its strength and toughness.

15. A process as defined in claim 14, in which the alloy is prepared to contain carbon in the range of about 0.20% to about 0.30%.

16. A process of making steel capable of providing high strength and high toughness, comprising: preparing, by melting into ingot form, an alloy having the composition defined in claim 1; said preparation including the step of melting an electrode which comprises the ingredients defined as aforesaid and additional carbon to remove excess oxygen, into said ingot form, said melting of the electrode being effected by passage of electric current, under a vacuum constituting a pressure of not more than 100 microns, so as to yield an ingot which has the aforesaid composition.

17. A process as defined in claim 16, wherein the alloy is prepared to have a composition containing not more than about 0.35% carbon.

18. A process of making steel capable of providing high strength and high toughness, comprising: preparing, by melting into ingot form, an alloy having the composition defined in claim 5; said preparation including the step of melting an electrode which comprises the ingredients defined as aforesaid and additional carbon to remove excess oxygen, into said ingot form, said melting of the electrode being effected by passage of electric current, under a vacuum constituting a pressure of not more than 100 microns, so as to yield an ingot which has the aforesaid composition.

19. A process as defined in claim 17, in which the preparation by melting includes a preceding step, for preparation of first-stage metal from which the electrode is derived, of open melting of ingredients defined as aforesaid to yield said first-stage metal by open pouring.

20. A process as defined in claim 19, in which the open melting is effected by electric arc furnace operation under open conditions and includes pouring the first-stage metal from said furnace operation, and while said first-stage metal remains molten, subjecting it to vacuum degassing.

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