

[54] HOT-ROLLED LOW ALLOY STEELS

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[22] Filed: May 11, 1970

[21] Appl. No.: 36,391

[52] U.S. Cl.148/12, 148/12.3, 148/36

[51] Int. Cl.C21d 7/14, C22c 39/30, C22c 39/54

[58] Field of Search.....148/12, 12.3, 12.4, 148/36

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[57] ABSTRACT

A high-strength, low alloy steel containing about 0.01 to about 0.1 percent carbon, about 1.5 to about 2.5 percent manganese, about 0.1 to about 0.5 percent molybdenum, about 0.05 to about 0.2 percent niobium, and the balance iron, as the essential alloying constituents along with the usual impurities in conventional amounts. The low alloy steel is further characterized as having a predominantly acicular-ferrite microstructure contributing toward its excellent combination of strength and impact resistance in the hot rolled and hot rolled plus aged conditions.

8 Claims, No Drawings

HOT-ROLLED LOW ALLOY STEELS**BACKGROUND OF THE INVENTION**

A number of structural steel compositions of the so-called low alloy type have heretofore been proposed for manufacture employing conventional mass production steel mill equipment and techniques. Such structural steels, in addition to being of high strength and impact toughness, are further characterized as being highly formable and weldable, facilitating the fabrication of various structural members therefrom. A continuing problem associated with such prior art low alloy steels has been the erratic and unpredictable variations obtained in their physical properties, including tensile strength, impact toughness and formability, particularly when fabricated in relatively thick gauges. In addition, some such prior art low alloy steels have necessitated the use of relatively elaborate rolling facilities and attendant controls to assure proper cooling of the hot-rolled strip produced in order to attain reasonable resultant physical properties. Attempts to overcome the foregoing problems by the further inclusion of appreciable amounts of additional alloying constituents has resulted in substantial increases in the cost of such structural steels, detracting from their more widespread use.

The forgoing problems and disadvantages are overcome in accordance with the novel low alloy steel comprising the present invention which is of a controlled chemical composition, enabling the attainment of an optimum combination of physical properties and which can be manufactured in the form of plate and strip stock employing conventional mass production steel mill facilities. The resultant hot-rolled plate and strip is characterized as having a predominantly acicular-ferrite micro-structure as distinguished from polygonal ferrite microstructures characteristic of prior art low alloy structural steels.

SUMMARY OF THE INVENTION

The benefits and advantages of the present invention are based on the discovery that by carefully controlling the amount of carbon, manganese, molybdenum and niobium, as the essential alloying constituents, a low alloy steel is provided which is readily adaptable to hot rolling for forming plate and coiled strip stock which is characterized by a microstructure having niobium carbonitride in the form of extremely fine-sized particles distributed through a predominantly acicular-ferrite matrix. The chemistry of the low alloy steel comprising the present invention is controlled so as to provide a carbon content of from about 0.01 to about 0.1 percent, manganese from about 1.5 to about 2.5 percent, molybdenum from about 0.1 to about 0.5 percent, niobium from about 0.05 to about 0.2 percent, silicon up to about 0.6 percent, sulfur up to 0.04 percent maximum, phosphorous up to 0.04 percent maximum, nitrogen up to 0.015 percent maximum, zirconium present in stoichiometric proportions for all nitrogen present in excess of about 0.008 percent to form the corresponding zirconium nitride, with the balance consisting essentially of iron along with conventional impurities present in amounts which do not significantly affect the physical properties and microstructure of the steel alloy. While the low alloy steel comprising the present discovery is particularly suitable for forming

hot-rolled plate stock usually ranging from about $\frac{3}{8}$ -inch to about one inch thick, it is also suitable for making steel strip of a thickness usually of $\frac{1}{4}$ -inch or less. In the fabrication of the hot-rolled plate and hot-rolled coiled strip, the slab, preliminary to hot rolling, is heated to a temperature sufficient to effect a solid solution of the niobium in the austenite. This temperature, in accordance with the compositions usable in the practice of the present invention, conventionally ranges from about 2250° F. to about 2350° F. The finishing temperature for rolling the plates is not critical but in the production of coil strip, it is important that the "coiling temperature," that is, the temperature of the steel strip as it enters the coiler at the end of the runout table, should not exceed about 1150° F. to about 1175° F. due to the adverse effect of higher temperatures on the attainment of the appropriate acicular-ferrite microstructure.

Additional benefits and advantages of the present invention will become apparent upon a reading of the description of the preferred embodiments taken in conjunction with the specific examples provided.

DESCRIPTION OF THE PREFERRED EMBODIMENTS

The combination of optimum physical properties of the low alloy steel comprising the present invention in the form of hot-rolled plate and coil strip stock is attained employing controlled proportions of carbon, manganese, molybdenum and niobium as the essential alloying constituents which are present in amounts expressed in terms of percentages by weight. The carbon content of the alloy may broadly range from about 0.01 to about 0.1 percent, and preferably is controlled within a range of from about 0.02 up to about 0.07 percent. Amounts of carbon in excess of about 0.1 percent are undesirable because of the formation of excessive amounts of a brittle martensite phase in the final rolled steel product which adversely affects the toughness and formability properties of the alloy, whereas amounts less than about 0.01 percent are economically impractical to attain and detract from the formation of sufficient amounts of precipitated niobium carbonitride in the final rolled stock. The quantity of manganese is controlled within a range of about 1.5 to about 2.5 percent in order to suppress the formation of polygonal ferrite during cooling of the hot-rolled plate. The presence of manganese also inhibits the premature precipitation of niobium carbonitride in the austenite prior to and during hot rolling of the slab or ingot. In the fabrication of hot-rolled plate, the manganese content is preferably maintained within a range of about 1.8 to about 2.2 percent; whereas in the manufacture of coiled strip, the manganese content is preferably controlled within the lower end of the permissible range, that is, from about 1.5 to about 2.0 percent for economic considerations. The third essential alloying constituent is molybdenum, which is present in an amount of about 0.1 to about 0.5 percent, which, within the aforementioned range, contributes to a suppression of polygonal ferrite formation during cooling of the hot-rolled stock. Preferably the molybdenum content is controlled within a range of about 0.18 to about 0.4 percent for both hot-rolled plate and coiled strip stock. The niobium constituent is controlled

within a range of about 0.05 to about 0.2 percent and within this range, provides for a suppression in the formation of polygonal ferrite and further provides for a strengthening of the resultant product in the form of precipitated particles of carbonitride in the acicular-ferrite structure. It is also believed that the presence of niobium in the specific amounts indicated has a grain refining effect on the austenite during hot-rolling operations. Preferably the niobium is controlled within a range of about 0.06 to about 0.1 percent.

The foregoing alloying constituents employed within the amounts indicated in combination with iron, along with conventional impurities in usual amounts, provides a low alloy steel which is predominantly of an acicular-ferrite microstructure avoiding the formation of excessive amounts of polygonal ferrite and further avoiding a retention of prior austenite grain boundaries when fabricated into hot-rolled plate up to one inch in thickness employing conventional air cooling practices. The acicular-ferrite substructure of the alloy is believed still further strengthened by a partial precipitation of niobium carbonitride during the cooling of the hot-rolled stock. Still further improvement in strength can be attained without any appreciable loss in toughness by effecting an additional precipitation of niobium carbonitride either by reducing the cooling rate after the transformation as in the case of coiled strip production or, alternatively, by stress relieving the rolled plates by reheating in the case of plate stock produced on a conventional plate mill.

The chemistry of the low alloy steel comprising the present invention enables a melting thereof by conventional open hearth, electric or basic oxygen processes. When melting the alloy in an environment containing nitrogen, the melting and/or handling of the alloy is controlled so as to maintain the net nitrogen content thereof at a level less than about 0.015 percent and preferably at a level of 0.007 percent. In those instances where the nitrogen content of the alloy is present in an amount above about 0.008 percent, it is preferred to add zirconium in stoichiometric amounts to form the corresponding zirconium nitride in order to control the nitride form in the austenite.

In addition to the foregoing constituents, the low alloy steel comprising the present invention may further include up to about 0.08 percent aluminum to achieve good deoxidation in accordance with conventional steel making practice, while amounts ranging from about 0.02 to about 0.05 percent are usually preferred. Sulfur and phosphorous are not desired and should be maintained at levels as low as commercially feasible; generally below 0.04 and preferably below 0.03 percent maximum. Silicon may also be present as an optional constituent in amounts up to about 0.35 percent, and preferably is kept as low as economically feasible.

In fabricating hot-rolled plates and coiled strip from ingots and slabs of the low alloy steel, it is important that the niobium is in solid solution in the austenite at the initiation of the hot-rolling operation, which requires ingot or slab reheat temperatures usually of about 2250° F. to about 2350° F. In reheating slabs preparatory to a final rolling operation, for example, the reheat temperature of the slab is preferably controlled at a minimum above that level at which the

niobium is present in a solid solution in the austenite since further heating to higher temperatures promotes grain growth in the slab. The temperature at which the finishing operation is performed on the hot-rolled plates is not critical. The hot rolling of the preheated ingot or slab to a coiled strip is performed under controlled cooling conditions to avoid any appreciable formation of polygonal ferrite in the final product. In the fabrication of hot-rolled plate stock, cooling rates corresponding to air cooling rates conventionally encountered in the fabrication of hot-rolled plate can be satisfactorily employed. Such air cooling rates are in the order of about 3° F. per second as measured on a ½-inch thick steel plate at a temperature of 1300° F.

In connection with the fabrication of coiled strip, the finishing temperature is important to the extent that it should be sufficiently low such that the "coiling temperature" should not exceed about 1150° F. to about 1175° F. due to an adverse effect on the mechanical properties and microstructure of the resultant strip.

In order to further illustrate the optimum combination of physical properties of low alloy steel made in accordance with the practice of the present invention, a series of steel alloy samples, designated as numbers 1 through 12, inclusive, were prepared and subjected to various physical tests. The compositions of the twelve individual alloy samples are provided in Table 1.

TABLE I
COMPOSITIONS (Weight percent)

| Steel No. | Carbon | Manganese | Silicon | Molybdenum | Niobium |
|-----------|--------|-----------|---------|------------|---------|
| 1 | 0.049 | 1.87 | 0.05 | 0.23 | 0.045 |
| 2 | 0.051 | 1.89 | 0.20 | 0.20 | 0.050 |
| 3 | 0.051 | 2.20 | 0.20 | 0.20 | 0.050 |
| 4 | 0.049 | 1.87 | 0.05 | 0.23 | 0.065 |
| 5 | 0.019 | 1.86 | 0.05 | 0.24 | 0.09 |
| 6 | 0.041 | 1.80 | 0.06 | 0.25 | 0.09 |
| 7 | 0.048 | 1.86 | 0.06 | 0.18 | 0.09 |
| 8 | 0.056 | 1.90 | 0.07 | 0.26 | 0.09 |
| 9 | 0.052 | 1.86 | 0.05 | 0.24 | 0.09 |
| 10 | 0.052 | 1.86 | 0.30 | 0.24 | 0.09 |
| 11 | 0.056 | 1.90 | 0.07 | 0.38 | 0.09 |
| 12 | 0.056 | 1.90 | 0.07 | 0.54 | 0.09 |

In addition to the specific ingredients present in the proportions as indicated in Table 1, each steel sample contained about 0.02 percent aluminum, about 0.005 percent nitrogen, about 0.01 percent phosphorous and about 0.01 percent sulfur. The balance of the alloys consisted essentially of iron with trace amounts of other impurities. The sample steels were prepared in laboratory quantities and processed in a manner simulating typical commercial production techniques. For the purposes of facilitating analyses of the physical strength and impact test data, steel samples 1-4, inclusive, have been generally categorized as compositions typical of those having a low niobium content; whereas steel samples 5-12, inclusive, have been categorized as being typical of compositions having a high niobium content.

Tensile test data, including yield strength (Y.S.), ultimate tensile strength (U.T.S.), percent elongation in one inch (% Elong.) and percent reduction of area (% Red.), and Charpy V-notch impact test data are set forth in Tables 2A and 2B on test specimens prepared

from several of the steel samples in an as-rolled as well as rolled and stress relieved condition, respectively. Unless otherwise specified, these data are based on specimens prepared from steel samples hot rolled to plates ranging from $\frac{3}{8}$ -inch to $\frac{5}{8}$ -inch in thickness, beginning at a temperature ranging between 2250° F. and 2350° F., and thereafter finished rolled at 1600° F. The axis of the test specimens was taken parallel to the direction of rolling, unless otherwise indicated, and the root of the V-notch was disposed perpendicular to the plane of rolling. The data as portrayed in Table 2B

Table 3 provides a comparison of tensile test and impact data of sample 6 steel as a function of plate thickness. In each instance, the plate was finish-rolled at 1600° F. and air cooled, and the test specimens were oriented in a direction parallel to the rolling direction. The tensile specimens from the 0.375-inch plates were of a diameter of 0.188 inch, and all the others were 0.250-inch in diameter. The specimens for Charpy impact evaluation from the 0.375-inch plates were of a width of 0.295-inch, and all the others were 0.394-inch wide.

TABLE 3

| Plate thickness (inches) | Tensile test data | | | | Charpy V-notch data | | | |
|------------------------------|---------------------------|-----------------|----------------|--------------|---------------------|--------------------|----------------------|-------------------------|
| | 0.2% offset Y.S. (K s.i.) | U.T.S. (K s.i.) | Percent elong. | Percent red. | Ft.-lb. at 75° F. | Ft.-lb. at -50° F. | 20 ft.-lb. temp.(F.) | 50% shear fracture (F.) |
| As-rolled | | | | | | | | |
| 0.375 | 70.5 | 95.4 | 23 | 79 | 151 | 73 | -95 | -50 |
| 0.500 | 70.8 | 94.6 | 27 | 76 | 132 | 34 | -50 | -20 |
| 0.625 | 69.1 | 94.5 | 27 | 78 | 160 | ND | -15 | 30 |
| Stress-relieved at 1,150° F. | | | | | | | | |
| 0.375 | 92.7 | 103.7 | 22 | 71 | 108 | 41 | -11 | -5 |
| 0.500 | 89.8 | 101.8 | 27 | 76 | 109 | ND | -15 | 20 |
| 0.625 | 86.7 | 100.2 | 29 | 76 | 100 | ND | 25 | 70 |

were obtained on stress relieved specimens which were stress relieved by holding the original samples at a temperature within 1100° F. to 1150° F. for a period of one hour, followed by air cooling. The use of "N.D." in these tables indicates that no determination of the value was made.

Table 4 provides tensile test data and impact data on several of the steel samples processed in a manner to simulate commercial production of coiled strip having a nominal thickness of $\frac{1}{4}$ -inch in which the coiling temperature was about 1150° F. Finish rolling of the strip was performed at 1600° F. The thermal effect of coiling

TABLE 2A

| Steel number | Tensile test data | | | | Charpy V-notch impact data | | | |
|---|---------------------------|-----------------|----------------|--------------|----------------------------|--------------------|-----------------------|-------------------------|
| | 0.2% offset Y.S. (K s.i.) | U.T.S. (K s.i.) | Percent elong. | Percent red. | Ft.-lb. at 75° F. | Ft.-lb. at -50° F. | 20 ft.-lb. temp. (F.) | 50% shear fracture (F.) |
| As-rolled, low-Nb (nominal Y.S.=60,000 p.s.i.) | | | | | | | | |
| 1 | 60.5 | 86.7 | 30 | 79 | 220 | 136 | -70 | -60 |
| 2 | 60.2 | 88.6 | 29 | 76 | 115 | ND | -15 | 35 |
| 2* | 62.2 | 90.0 | 29 | 76 | 188 | ND | -15 | 25 |
| 3 | 65.5 | 96.3 | 26 | 72 | 124 | 10 | -20 | 30 |
| As-rolled, high-Nb (nominal Y.S.=70,000 p.s.i.) | | | | | | | | |
| 5 | 68.1 | 89.1 | 31 | 80 | 224 | 171 | -90 | -65 |
| 7 | 68.1 | 98.9 | 26 | 73 | 125 | 13 | -20 | 20 |
| 6** | 70.1 | 95.0 | 27 | 77 | 101 | 20 | -50 | -10 |
| 6 | 70.8 | 94.6 | 27 | 76 | 132 | 34 | -55 | -20 |
| 8 | 70.9 | 99.8 | 26 | 74 | 163 | 18 | -40 | 40 |
| 12 | 73.1 | 105.0 | 24 | 71 | 139 | 19 | -45 | 30 |

* Tensile and impact specimen axes perpendicular to rolling direction.

** Finished-rolled at 1,800° F. instead of 1,600° F.

TABLE 2B

| Steel number | Tensile test data | | | | Charpy V-notch impact data | | | |
|---|---------------------------|-----------------|----------------|--------------|----------------------------|--------------------|-----------------------|-------------------------|
| | 0.2% offset Y.S. (K s.i.) | U.T.S. (K s.i.) | Percent elong. | Percent red. | Ft.-lb. at 75° F. | Ft.-lb. at -50° F. | 20 ft.-lb. temp. (F.) | 50% shear fracture (F.) |
| Stress-relieved, low-Nb (nominal Y.S.=75,000 p.s.i.) | | | | | | | | |
| 2 | 77.5 | 91.3 | 29 | 76 | 169 | ND | 0 | 30 |
| 1 | 78.3 | 89.3 | 31 | 80 | >240 | 178 | -100 | -75 |
| 2* | 79.2 | 95.3 | 28 | 76 | 124 | 10 | -15 | 5 |
| 4 | 81.0 | 93.1 | 30 | 77 | 169 | 21 | -50 | -25 |
| 4 | 81.9 | 95.0 | 28 | 73 | 190 | 7 | -30 | -20 |
| 3* | 84.4 | 101.4 | 25 | 72 | 113 | ND | -40 | 15 |
| Stress-relieved, high-Nb (nominal Y.S.=85,000 p.s.i.) | | | | | | | | |
| 5 | 84.8 | 95.3 | 30 | 79 | 219 | 150 | -85 | -50 |
| 10 | 87.5 | 101.7 | 27 | 75 | 102 | 7 | -35 | 35 |
| 8 | 89.4 | 103.8 | 27 | 74 | 132 | 8 | -10 | 25 |
| 9 | 89.6 | 101.3 | 28 | 75 | 142 | 8 | -40 | 59 |
| 6 | 89.8 | 101.8 | 27 | 76 | 100 | ND | -45 | 20 |
| 6** | 90.6 | 102.7 | 26 | 76 | 160 | ND | -30 | 0 |
| 11 | 91.7 | 107.5 | 25 | 72 | 108 | 6 | -10 | 55 |
| 12 | 93.2 | 100.4 | 26 | 71 | 142 | 4 | -10 | 0 |

* Tensile and impact specimen axes perpendicular to rolling direction.

** Finish-rolled at 1,800° F. instead of 1,600° F.

was simulated by program-cooling in an air-recirculating furnace, using a cooling rate of 40° F. per hour. The data provided with respect to percent of elongation was measured over a two-inch length.

3. The alloy steel article as defined in claim 1 consisting essentially of about 0.02 to about 0.07 percent carbon, about 1.8 to about 2.2 percent manganese, about 0.18 to about 0.4 percent molybdenum, about 0.06 to

TABLE 4

| Steel number | Tensile test data | | | Half-size Charpy V-notch data | | | | |
|--------------|---------------------------|-----------------|----------------|-------------------------------|------------------|--------------------|-----------------------|-------------------------|
| | 0.2% offset Y.S. (K s.i.) | U.T.S. (K s.i.) | Percent elong. | Ft.-lb. at 75° F. | Ft.-lb. at 0° F. | Ft.-lb. at -50° F. | 10 ft.-lb. temp. (F.) | 50% shear fracture (F.) |
| 1 | 70.8 | 84.3 | 22 | 73 | 69 | 40 | -130 | -60 |
| 1* | 72.3 | 84.5 | 24 | 61 | ND | 26 | -115 | -45 |
| 3 | 67.3 | 85.3 | 23 | 62 | 50 | 44 | -70 | -30 |
| 3* | 67.4 | 85.7 | 21 | 60 | ND | 32 | -70 | -30 |
| 2 | 71.7 | 86.6 | 22 | 70 | 54 | 44 | -90 | -50 |
| 2* | 74.3 | 88.5 | 20 | 61 | ND | 28 | -75 | -40 |
| 5 | 81.9 | 93.5 | 22 | 74 | 39 | 43 | -90 | -40 |
| 5* | 83.9 | 94.1 | 21 | 46 | ND | 26 | -70 | -40 |

*Transverse tensile and impact properties.

In addition to the foregoing, specimens of steel strip derived from samples 1 and 5 were observed to exhibit excellent bendability, enabling transverse specimens to be bent through an angularity of 180° around a ¼-inch diameter mandrel and thereafter further flattened without evidencing any cracking or fracture thereof. Specimens of steel samples 1 and 5 were also welded utilizing a manual arc welding technique which formed a sound weld of sufficient ductility to enable bending thereof through an angularity of 90 degrees without fracture. A traverse taken across a polished section of the weld to determine the microhardness thereof evidenced the absence of any hard or soft zones adjacent to the weld line.

While it will be apparent that the invention herein disclosed is well calculated to achieve the benefits and advantages as hereinabove set forth, it will be appreciated that the invention is susceptible to modification, variation and change without departing from the spirit thereof.

What is claimed is:

1. A hot rolled alloy steel article consisting essentially of about 0.01 to about 0.1 percent carbon, greater than 1.5 up to about 2.5 percent manganese, about 0.1 to about 0.5 percent molybdenum, about 0.05 to about 0.2 percent niobium, up to about 0.08 percent aluminum, up to about 0.015 percent nitrogen and zirconium present in a stoichiometric amount to form the corresponding zirconium nitride with that amount of nitrogen present in excess of about 0.008 percent, up to a maximum of 0.04 percent sulfur, up to a maximum of 0.04 percent phosphorous, and the balance iron, said steel further characterized as having a microstructure comprised of a predominantly acicular-ferrite matrix, and substantially devoid of any prior austenite grain boundaries, said alloy steel article in an as-rolled condition having a Charpy V-notch impact value of at least about 100 ft-lb at 75° F. as measured on a standard test specimen and a 0.2 percent offset yield strength of at least about 60 ksi.

2. The alloy steel article as defined in claim 1, further characterized by precipitated niobium carbonitride particles dispersed throughout the predominantly acicular-ferrite matrix.

about 0.1 percent niobium, from about 0.02 to about 0.05 percent aluminum, up to about 0.007 percent nitrogen, up to a maximum of 0.03 percent sulfur and up to a maximum of about 0.03 percent phosphorous.

4. The alloy steel article as defined in claim 1 in the form of a hot-rolled plate.

5. The alloy steel article as defined in claim 1 in the form of a hot-rolled coiled strip having a Charpy V-notch longitudinal impact value of at least about 62 ft-lb at 75° F. as measured on a half-size test specimen and a 0.2 percent offset yield strength of at least about 67 ksi.

6. The method of making a low-alloy steel plate which comprises the steps of forming a solidified mass of an alloy consisting essentially of about 0.01 to about 0.1 percent carbon, greater than 1.5 up to about 2.5 percent manganese, about 0.1 to about 0.5 percent molybdenum, about 0.05 to about 0.2 percent niobium, up to about 0.08 percent aluminum, up to about 0.015 percent nitrogen and zirconium present in a stoichiometric amount to form the corresponding zirconium nitride with that amount of nitrogen present in excess of about 0.008 percent up to a maximum of 0.04 percent sulfur, up to a maximum of 0.04 percent phosphorous and the balance iron; heating said mass to an elevated temperature sufficient to form a solid solution of substantially all of the niobium in an austenitic structure, deforming said mass while at said elevated temperature, air cooling the deformed said mass through the transformation range, which will avoid the formation of appreciable amounts of polygonal ferrite, forming a microstructure comprised of precipitated niobium carbonitride particles dispersed throughout a predominantly acicular-ferrite matrix and which microstructure is substantially devoid of any prior austenite grain boundaries.

7. The method as defined in claim 6, wherein said elevated temperature ranges from about 2250° F. to about 2350° F.

8. The method as defined in claim 6, in which the cooled and deformed said mass is subjected to the further step of stress relieving by heating it for a period of time at a temperature of about 1100° F. to about 1200° F. sufficient to effect stress relieving and a further precipitation of niobium carbonitride particles throughout said acicular-ferrite structure.

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