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HIGH STRENGTH ALLOY STEELS

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This invention relates to improvements in high strength alloy steels and more particularly to a steel suitable for use where ultra high strength is desirable for weight saving, as well as where high strength must be maintained for prolonged periods of elevated temperatures, and is an improvement upon the alloy of my copending application Serial No. 800,663, filed March 20, 1959, in that with the present invention the stress rupture and elevated temperature properties are materially increased.

Heretofore low alloy steels, due to temper brittleness, have never been suitable for ultra-high strength applications, and in order to get a low alloy material in strength levels above 180,000–200,000 p.s.i. tensile it has heretofore been necessary to temper in a temper-brittle range where ductility was detrimentally affected.

A general object of the invention is to provide an improved alloy steel which has only a nominal total alloy content whereby it uses only a minimum of strategic materials, making it economically desirable.

A further object of the invention is to provide an alloy steel as above described which is capable of being heat treated to ultra-high strength levels while maintaining adequate ductility, particularly transverse ductility.

A further object of the invention is to provide an alloy steel which is suitable for use where superior toughness, wear resistance, elevated temperature strength, and high impact load resistance are necessary, making it particularly suitable for elevated temperature structural applications.

A further object of the invention is to provide an alloy steel which exhibits superior properties at room temperature when heat treated to a predetermined high tensile strength range, the alloy retaining sufficient toughness so that it can be used for missile and aircraft structural applications and having excellent elevated temperature properties when heat treated to a predetermined tensile strength range.

A further object of the invention is to provide an alloy steel which maintains a high yield to ultimate ratio at all strength levels up to 280,000 p.s.i. ultimate.

Other objects are to provide an alloy steel which exhibits less distortion in quenching, and which is weldable in heavy sections while employing techniques and control normally used in welding medium carbon low alloy materials with high hardenability.

A further object of the invention is to provide improvements in the processing of an alloy steel of the class described.

In carrying out the invention it has been discovered that a relatively high carbon range can be used in the formula without causing brittleness while the product maintains ductility and good weldability.

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The alloy of this invention has the following contents in percent:

C	40–50.
5 Mn	58–93.
Si	13–32.
Ni	35–75.
Cr	87–1.23.
Mo	88–1.12.
10 P	.010 maximum.
S	.010 maximum.
V	.20–1.00.
Remainder iron with incidental impurities.	

It is important to maintain the phosphorous and sulphur content relatively low. The nickel content is always less than chromium content and is always less than the molybdenum content. In my copending application Serial No. 800,663, a small amount of vanadium has been used to control the grain size, this amount, however, being kept so low as not to affect the essential properties of the alloy. In the invention of the present application it has been found that the use of a substantially larger amount of vanadium as specified has a surprising effect on the essential properties and appreciably increases the elevated temperature and stress rupture properties.

A desirable formula for many purposes is:

C	.46 approximate.
30 Mn	.75 approximate.
Si	.22 approximate.
Ni	.55 approximate.
Cr	1.00 approximate.
Mo	1.00 approximate.
35 P	.010 maximum.
S	.010 maximum.
V	.50 approximate.
Remainder iron with incidental impurities.	

The above formula may be modified by the addition of other elements and the present invention is not to be construed so as to preclude the use of small amounts of such additional elements as uranium 238, boron, or rare earth elements in the basic composition.

It is apparent from the above total that the alloy content is very low so that only a minimum of strategic materials need be employed to obtain properties heretofore obtained only by a much higher alloy content.

In manufacturing the improved alloy, alloying agents are added at the steel mill in accordance with the above formula, except that when there is to be a vacuum arc consumable electrode remelt the amount of manganese is chemically adjusted at a higher level, for example, between .95–1.20 to allow for losses. While an air melt process produces a satisfactory alloy, transverse ductility and other properties can be substantially improved by use of a vacuum arc consumable electrode remelt furnace process. When this process is used the alloy after being through an air melt process and in ingot form is rolled to billet form to fit a consumable electrode furnace in the mill. It is then remelted in a vacuum arc consumable electrode remelt furnace and during such remelting it loses the excess manganese to provide a final manganese content like that listed in the formula above. The vacuum arc consumable electrode remelt furnace has a purging effect on lighter impurities, which can then be

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eliminated, so that the number and size of the impurities from the air melt are greatly reduced. Those impurities which remain are smaller and better distributed. As a result, the alloy is much cleaner and has improved transverse ductility and other properties.

The following tables indicate the improved properties of the alloy steel of the present invention:

An average of the room temperature mechanical properties of the present alloy steel after normalizing at 1650° F., and oil quenching from 1550° F., and tempering as shown are summarized in Table I. The maximum ultimate and yield strength with adequate ductility as measured by percent elongation and reduction of area is achieved by tempering between 500° F. and 700° F. This temper produces an ultimate tensile strength of 255,000 to 285,000 p.s.i., a yield strength of 235,000 to 249,000 p.s.i., elongation of 7.0 to 10% and an Izod impact of 20.0 ft. lbs. The present alloy steel shows no "blue brittle" range when tempered from 300° F. to 1200° F. and tested at room temperature. Ultimate strengths of over 300,000 p.s.i. have been reached at some of the lower tempering temperatures.

TABLE I

Mechanical properties at room temperature

Temper Temp., ° F.	U.S., p.s.i.	Y.S., p.s.i.	Percent Elong. in two inches	Percent Red. of Area	Rockwell "C" Hardness	Izod Impact, ft. lbs.
300.....	298,624	210,700	8.5	19.0	56	9.0
400.....	288,000	235,090	8.9	25.7	55.5	14.7
500.....	284,320	249,840	7.5	26.8	53.5	20.0
600.....	266,970	246,920	8.1	30.0	54.0	-----
700.....	255,950	241,500	8.5	32.3	51.5	-----
800.....	236,150	228,000	9.6	36.8	50.5	26.7
900.....	223,100	220,010	10.6	42.4	50.0	34.7
1,000.....	217,100	210,810	13.0	45.5	48.0	37.1
1,100.....	200,500	193,030	14.2	49.1	47.5	52.6
1,200.....	150,120	140,760	18.4	60.8	39.0	63.4

SHORT TIME ELEVATED TEMPERATURE PROPERTIES

Short time elevated temperature properties of the alloy steel of the present invention when tempered at 50° F. above the test temperature are summarized in Table II. These temperatures are 50° F. below the corresponding temper temperatures to simulate treatment necessary to be compatible with operating temperatures, i.e. the tempering temperature must be higher than the operating temperature to prevent tempering the material while in operation.

The elevated temperature data shows the yield and ultimate strength to be well above 140,000 p.s.i. to 900° F. test temperature. With these high elevated temperature properties the present alloy is desirable for elevated temperature structural applications. This data is indicative of properties obtainable when designing to operating temperature ranges.

TABLE II

Short time elevated temperature properties

[Normalize 1,650° F.; oil quench 1,550° F.; temper 50° F. above the test temperature—average of 5 tests.]

Test Temperature, ° F.	Ultimate Strength, p.s.i.	Yield Strength, p.s.i. (0.2% offset)	Percent Elongation in two inches	Percent Red. of Area
400.....	279,900	198,000	14.7	43.0
500.....	254,100	184,000	15.8	53.2
600.....	231,540	173,180	15.9	58.3
700.....	209,110	175,440	14.2	56.0
800.....	187,500	160,050	15.9	59.4
900.....	165,750	146,250	16.5	63.6
1,000.....	142,550	118,800	20.6	70.7
1,100.....	84,280	70,820	29.7	86.0
1,200.....	43,150	33,560	52.1	90.2

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SHORT TIME ELEVATED TEMPERATURE PROPERTIES AT STRENGTH LEVELS OF 180,000-200,000 P.S.I.; 200,000-220,000 P.S.I.; AND 220,000-240,000 P.S.I.

The data in Table III-A, B, and C shows additional elevated temperature properties for the above three strength levels. One inch diameter bars were normalized at 1650° F., oil quenched from 1550° F. and tempered at 950° F., 1050° F., and 1150° F. respectively. The ductility as measured by percent elongation increases uniformly as the test temperature is increased. Since the yield strength is held well above 100,000 p.s.i. at 900° F. at all three strength levels, this makes the present alloy desirable for high temperature structural applications.

TABLE III(A)

180,000-200,000 p.s.i. strength level—tempered at 1150° F.

Test Temperature, ° F.	Ultimate Strength, p.s.i.	Yield Strength, p.s.i. (0.2% offset)	Percent Elongation in two inches	Percent Red. of Area
80.....	193,500	188,300	14.0	53.4
500.....	178,900	148,960	16.0	52.7
700.....	163,300	136,600	18.0	65.2
800.....	152,800	130,700	17.5	68.4
900.....	133,800	117,400	19.0	71.1
1,000.....	118,100	106,000	25.0	80.6
1,100.....	91,000	77,600	25.0	79.5

TABLE III(B)

200,000-220,000 p.s.i. strength level—tempered at 1050° F.

Test Temperature, ° F.	Ultimate Strength, p.s.i.	Yield Strength, p.s.i. (0.2% offset)	Percent Elongation in two inches	Percent Red. of Area
80.....	226,500	218,300	11.5	45.8
500.....	207,000	174,300	14.5	48.2
700.....	199,400	169,500	17.0	62.5
800.....	178,700	147,750	18.0	65.8
900.....	172,100	144,930	15.0	64.4
1,000.....	142,120	120,580	16.5	74.0

TABLE III(C)

200,000-240,000 p.s.i. strength level—tempered at 950° F.

Test Temperature, ° F.	Ultimate Strength, p.s.i.	Yield Strength, p.s.i. (0.2% offset)	Percent Elongation in two inches	Percent Red. of Area
500.....	213,800	176,600	15.0	55.7
700.....	193,300	156,600	14.5	61.1
800.....	188,900	165,800	15.5	61.9
900.....	167,400	144,800	17.5	64.7

ELEVATED TEMPERATURE IMPACT PROPERTIES

Charpy V-notch impact properties heat treated to 200,000 to 220,000 p.s.i. strength level and tested at elevated temperatures are shown in Table IV.

TABLE IV

Test Temp., ° F.	1, foot pounds	2, foot pounds	3, foot pounds	Average, ft. lbs.
80.....	34.0	46.0	40.0	40.0
500.....	42.5	46.5	46.0	45.0
700.....	46.0	41.5	41.5	43.0
800.....	54.0	55.0	48.5	52.5
900.....	40.0	41.5	46.5	46.0
1,000.....	35.5	39.0	35.5	36.6

LOW TEMPERATURE CHARPY V-NOTCH IMPACT TESTS

The apparent need for information on low temperature impacts at ultra-high strength levels and the possibility of a transition temperature prompted the low temperature impact testing from 70° F. down to -320° F. The data listed in Table V shows the results of these

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tests with no apparent transition down to -320°F . The fracture is completely tough and fibrous with an average impact value of 11.2 ft. lbs. at -210°F . A standard (.505") tensile was heated with the Charpy V-notch specimens as follows: Normalize at 1650°F . oil quench from 1550°F . temper at 600°F . Results of the tensile were: Ultimate strength 271,000 p.s.i.; 0.2% offset yield strength 254,500 p.s.i.; elongation 9.5% in 2 inches; reduction of area 36.0%.

TABLE V

Low temperature Charpy impact properties
(260,000–280,000 p.s.i. strength levels)

Test Temp., ° F.	Average 3 Tests, ft. lbs.	Test Temp., ° F.	Average 3 Tests, ft. lbs.
70.....	15.7	-90.....	14.0
50.....	15.2	-105.....	12.3
30.....	15.3	-120.....	12.7
10.....	15.7	-135.....	11.7
0.....	14.8	-150.....	12.5
-10.....	15.3	-165.....	11.5
-30.....	14.3	-180.....	11.2
-50.....	14.5	-195.....	10.3
-65.....	15.3	-210.....	11.2
-70.....	15.5	-320.....	5.2
-75.....	15.0		

ENDURANCE LIMIT

The fatigue life comparing the alloy of the present invention and a known alloy AISI-4340 is shown in Table VI. The specimens were heat treated to 260,000 p.s.i. strength level and show an endurance limit of 118,000 p.s.i. observed at 10,000,000 cycles.

TABLE VI

Fatigue Life	Alloy of present invention, 260,000 p.s.i. Tensile	AISI 4340, 260,000 p.s.i. Tensile
	p.s.i.	p.s.i.
100,000 cycles.....	130,000	125,000
1,000,000 cycles.....	119,000	100,000
10,000,000 cycles.....	118,000	95,000

ELEVATED TEMPERATURE STABILITY

The high temperature stability of the present alloy is summarized in Table VII. The ultimate strength ranges from 200,000 to 220,000 p.s.i. with uniform ductility as measured by percent elongation and reduction of area even after 100 hours of stabilizing at 1000°F .

TABLE VII

Procedure used in tensile stability tests

Normalize 1650°F .
Oil quench 1550°F .
Temper @ 1050°F .
Average of 3 room temperature tests after holding at time and temperature indicated.

Hours at $1,000^{\circ}\text{F}$. Stabilize	Ultimate Strength, p.s.i.	Yield Strength, p.s.i. (0.2% offset)	Percent Elonga- tion in 2 inches	Percent Red. of Area
0.....	215,730	207,500	13.5	49.2
10.....	215,000	205,500	13.9	49.4
100.....	205,000	195,700	13.2	48.3
100+10 hours at $1,050^{\circ}\text{F}$.	201,000	195,000	14.0	50.1

STRESS RUPTURE PROPERTIES

The stress rupture properties of the improved alloy heat treated to 200,000 to 220,000 p.s.i. strength level are shown in Table VIII. The properties are excellent up to

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900°F . test temperature and stresses up to 100,000 p.s.i. The material may be used where applications of high temperature and stress are required for prolonged periods of time.

- Stress for 1000 hours' rupture life at 900°F .—104,000 p.s.i.
Stress for 1000 hours' rupture life at 1000°F .—34,000 p.s.i.
Stress for 100 hours' rupture life at 1000°F .—66,000 p.s.i.

TABLE VIII

Stress, p.s.i.	$1,000^{\circ}\text{F}$. Test Temp., Hrs. to Fracture	Stress, p.s.i.	900°F . Test Temp., Hrs. to Fracture
40,000.....	577.1	70,000.....	3,682
50,000.....	254.2	80,000.....	3,964
60,000.....	156.0	90,000.....	2,166
70,000.....	80.2	100,000.....	1,029
80,000.....	42.0		

NOTCH TENSILE PROPERTIES

Notch tensile heat treat response for the alloy of the present invention is shown on Table IX. Notch specimens were normalized at 1700°F ., oil quenched from 1550°F . and tempered as shown. The tensiles had a Neuber stress concentration factor of 4.2. The results show a notch tensile strength of 50,000 to 70,000 p.s.i. higher than the un-notched properties of Table I.

TABLE IX

Temper Temp., ° F.	Notch Tensile Strength	Temper Temp., ° F.	Notch Tensile Strength
300.....	332,500	800.....	361,000
400.....	341,530	900.....	314,600
500.....	317,000	1,000.....	311,900
600.....	305,800	1,100.....	289,800
700.....	318,800	1,200.....	218,000

NOTCH TOUGHNESS

Additional notch tensile properties as compared to un-notched tensile are shown in Table X. The tensiles were normalized at 1650°F ., oil quenched from 1550°F ., and tempered as shown. A Neuber stress concentration factor of 4.2 was used on the notched tensiles.

TABLE X

Temper Temp., ° F.	Smooth Bars (Ave.)				Notch Bars (Ave.)
	Ultimate Strength, p.s.i.	Yield Strength, p.s.i. (0.2% offset)	Percent Elonga- tion in 2 inches	Percent Red. of Area	Notch Tensile Strength, p.s.i.
600.....	268,600	242,750	9.4	34.7	316,600
900.....	225,570	220,170	13.3	45.1	323,700
1,100.....	169,320	162,570	16.3	53.6	257,170

NOTCH TENSILE PROPERTIES WHEN HEAT TREATED TO ULTRA-HIGH STRENGTH

Notch tensile properties were studied by varying the specimen size, the strength level, and the stress concentration factor to determine the notch sensitivity as measured by the notched tensile tests at three strength levels.

Test specimen dimensions with stress concentration

factors and corresponding notch radii are shown in the following table:

Major Diameter, Inches	Notch Diameter, Inches	Notch Root Radius, Inches	K—According to Neuber
.300	.212	.011	K=3
		.0035	K=5
.500	.353	.018	K=3
		.006	K=5
.900	.636	.0342	K=3
		.0100	K=5

The results obtained with the above specimen sizes are summarized in Table XI. The notch tensile test is a good measure of the notch sensitivity and is probably a better criterion than the V-notch impact test. The extremely high ultimate strengths exhibited by the notched bars is due to the fact that the calculation is based upon the minor diameter of the notch, rather than the area of the major diameter. In contrast to this, a normal tensile calculation is based on the original diameter rather than the reduced cross sectional area after the tensile fracture.

TABLE XI

Major Diameter, Inches	Temperature, ° F.	K=3 ¹ Notch Tensile Strength, p.s.i.	K=5 ¹ Notch Tensile Strength, p.s.i.
.300	400	361,700	334,000
.300	400	378,000	320,500
.300	400	381,000	327,000
Average		373,600	327,200
.500	400	356,400	298,300
.500	400	339,500	296,800
.500	400	354,800	326,800
Average		350,200	307,300
.900	400	314,000	256,800
.900	400	333,000	276,500
.900	400	342,800	274,500
Average		329,900	269,300
.300	600	347,500	337,000
.300	600	340,000	319,000
.300	600	346,500	324,500
Average		344,700	326,800
.500	600	339,800	271,000
.500	600	331,200	275,000
.500	600	324,700	277,400
Average		331,900	274,500
.900	600	300,000	250,000
.900	600	304,800	248,000
.900	600	306,000	257,500
Average		303,600	251,800
.300	800	330,500	321,200
.300	800	334,000	323,500
.300	800	341,000	324,200
Average		335,200	323,000
.500	800	324,800	299,800
.500	800	329,400	288,300
.500	800	322,400	282,100
Average		325,500	290,100
.900	800	302,900	254,000
.900	800	318,300	270,000
.900	800	311,900	262,000
Average		311,000	262,000

¹ Neuber stress concentration factor.

EFFECT OF STRAIN AGING ALLOY OF PRESENT INVENTION

The mechanical properties as summarized in Table XII are the results of strain aging. Test results indicate that strain aging may offer a possibility of increase in tensile strength and yield strength above normal with an accompanying decrease in ductility. Subsequent stress relieve

temperatures should be low (less than 600° F.) and preferably below the original temper temperature. The test results show an increase in yield to ultimate ratio over standard tensile results tested at various tempering temperatures. For example, the yield to ultimate ratio for the unstrained alloy of the present invention at 500° F. is .88 as compared to .92 for the strained tensiles.

TABLE XII

Initial Temper., ° F.	Stress Relieve, ° F.	Ultimate Strength, p.s.i.	Yield Strength, p.s.i. (0.2% offset)	Percent Elongation in 2 inches	Percent Red. of Area
15 300	250	366,000	352,500	4.5	23.0
400	350	354,000	333,800	5.0	24.9
500	450	322,000	298,200	3.0	15.3
600	550	312,000	290,600	3.8	15.0
700	550	302,000	(1)	3.5	-----
800	550	279,000	266,800	2.5	19.4
900	550	256,100	256,100	4.0	37.6
1,000	550	241,900	237,900	6.0	42.6
20 1,100	550	212,300	211,900	8.5	46.0
1,200	550	156,400	150,400	9.0	53.7

¹ Fracture outside gauge marks.

It will be understood that it is desired to comprehend within the invention and the scope of the claims thereof such equivalent materials and proportions as may be found necessary to adapt this invention to the varying conditions met in actual practice and we do not limit ourselves to these specific materials and proportions.

What I claim is:

1. An improved alloy steel which contains about .40-.50% carbon, about .58-.93% manganese, about .13-.32% silicon, about .35-.75% nickel, about .87-1.23% chromium, about .88-1.12% molybdenum, up to about .010% phosphorous, up to about .010% sulphur, and there being .20 to 1.00% vanadium, and the remainder being iron with incidental impurities, and the metal being characterized by its ability to maintain high strength considering its low alloy content for prolonged periods of elevated temperatures with accompanying good ductility, there being an absence of temper brittleness when tempered at low tempering temperatures, and the metal being characterized by substantially increased elevated temperature and stress rupture properties.

2. An improved alloy steel which contains approximately .46% carbon, about .58-.93% manganese, about .13-.32% silicon, about .35-.75% nickel, about .87-1.23% chromium, about .88-1.12% molybdenum, up to about .010% phosphorous, up to about .010% sulphur, and approximately .50% vanadium, and the remainder being iron with incidental impurities, and the metal being characterized by its ability to maintain high strength considering its low alloy content for prolonged periods of elevated temperatures with accompanying good ductility, there being an absence of temper brittleness when tempered at low tempering temperatures, and the metal being characterized by substantially increased elevated temperature and stress rupture properties.

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