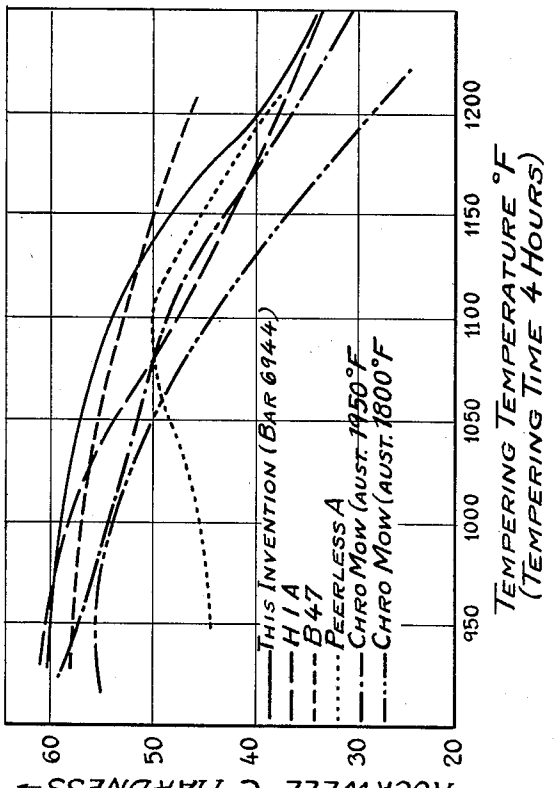
June 4, 1963 P. PAYSON ETAL 3,092,491

HIGH STRENGTH ALLOY STEEL FOR ATMOSPHERIC AND ELEVATED TEMPERATURE SERVICE

Filed May 2, 1957 2 Sheets-Sheet 1

	C	Mn	Si	Ni	Cr	V	Mo	Co	W
This Invention (Bar 6944)	0.41	0.62	1.0	—	3.2	0.32	2.8	—	—
B-47	0.40	0.25	0.50	—	4.25	2.0	—	4.25	—
Peerless A	0.28	0.30	0.20	—	3.25	0.25	—	—	8.75
H1A	0.38	0.79	0.90	2.15	5.82	0.32	3.85	—	—
Chro Mow	0.33	0.48	1.05	0.11	4.90	—	1.18	—	1.14

Fig. 1.



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HIGH STRENGTH ALLOY STEEL FOR ATMOSPHERIC AND ELEVATED TEMPERATURE SERVICE

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	4340	UHS 260	HALMO	THIS INVENTION
C	.40	.36	.32	.38
MN	.70	1.30	.30	.50
SI	.30	1.65	.60	1.00
NI	1.70	—	—	—
CR	.80	1.25	5.30	3.40
V	—	.20	.75	.30
MO	.25	.35	5.10	2.60
AUST. TEMP.	1550 450	1700 600	1950 1050	1950 1000

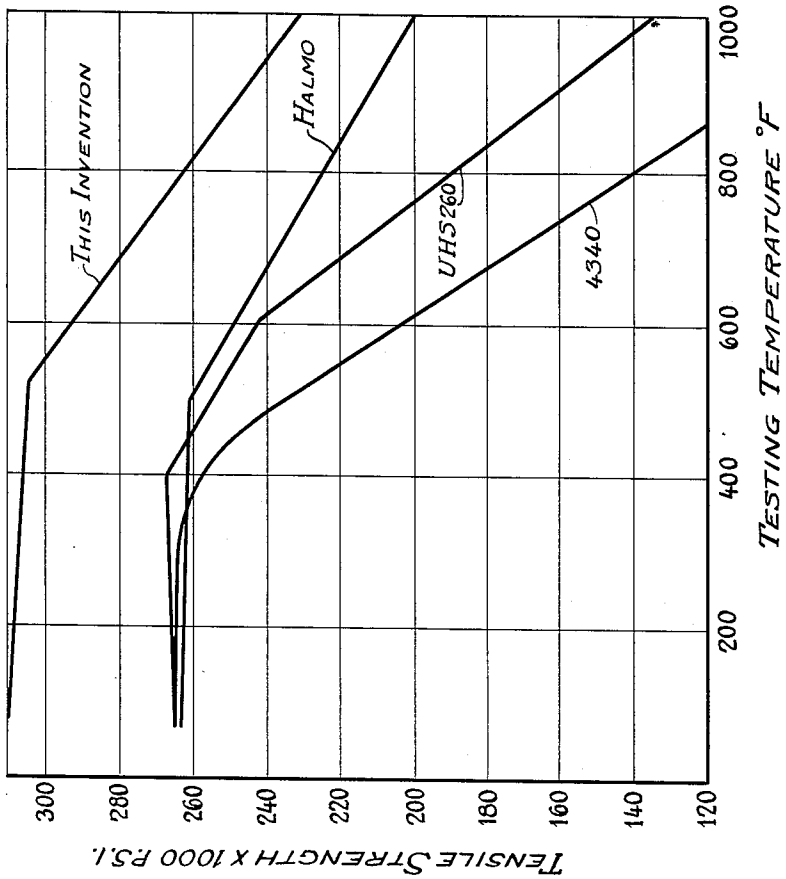

Fig. 2.

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HIGH STRENGTH ALLOY STEEL FOR ATMOSPHERIC AND ELEVATED TEMPERATURE SERVICE

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3 Claims. (Cl. 75—126)

This invention pertains to an alloy steel, of low total alloy content, containing in addition to carbon, as the only essential alloying constituents, manganese, silicon, chromium, vanadium and molybdenum, in critically limited amounts of each and proportions such as to impart to the steel on appropriate heat treatment as set forth below, a tensile strength at room temperature of at least 290,000 p.s.i. and at 1100° F. of at least 150,000 p.s.i. together with good tensile elongation and a reduction of area of at least 28% at room and elevated temperatures up to 1100° F., said steel being also characterized by excellent toughness and impact resistance at room and elevated temperatures.

There has arisen a need in the aircraft industry for steels of very high strength not only at room temperature but at temperatures as high as 1000° F. or even higher. When aircraft are flown at extremely high speeds of the order of Mach 2 to Mach 5, i.e., 2 to 5 times the speed of sound, very high temperatures are generated at the surface of the aircraft because of aerodynamic heating. It has been stated that a rough rule for estimating the temperatures generated (measured on the Fahrenheit scale) is to square the Mach number and multiply by 70. Thus for Mach 3, the expected temperature is about 630° F. and for Mach 4, about 1120° F.

Since aircraft must have a minimum of dead weight, it is necessary that materials of construction have very high strength so that the load carrying section may be reduced to a minimum. For service under appreciable stress at temperatures as high as 1100° F. and higher, the only commercial materials available are the steels, the nickel-base alloys, and the cobalt-base alloys, and of these, the lease expensive, and the most readily available, strategically, are the steels.

It is an object of this invention to provide low alloy steel having very high strength at room temperature and the ability to retain a large portion of this strength at temperatures up to at least 1000° F., such strength to be developed in the steel by a simple heat treatment. It is a further object of this invention to provide a very high strength steel of relatively low alloy content, free from the strategic elements nickel, cobalt, tungsten, and columbium. It is an additional object of this invention, to provide a low alloy steel of very high strength which also has adequate ductility, excellent toughness and low notch sensitivity.

Also, because steel of the above-mentioned characteristics has properties desirable for tools for working metals at high temperature, it is a further important object of this invention to provide a low alloy hot work tool steel or excellent toughness and relatively low cost.

Since toughness is a very important consideration in the serviceability of a structural steel at a very high strength level, as well as in hot work tools, we limit the carbon in our steel to a level commensurate with a hardness of Rockwell "C" 52 to "C" 60. In a publication by Nehrenberg, Payson and Lillys, Trans. ASM, vol. 47, 1955, page 785, it is shown that steel containing about

0.35 to 0.45% carbon when heat treated to a completely martensitic structure has hardness between about Rockwell "C" 58 and "C" 65. We accordingly use a carbon range of 0.35 to 0.45%, and preferably 0.38 to 0.43%, in the steel of this invention.

In order to provide high hardenability in the steel so that parts of relatively small section, for example, sheets for the "skin" of aircraft, can be hardened adequately, with a minimum of warpage, by an air cool, and so that parts of relatively large section, such as aircraft landing gear as well as tools for hot working applications, can be fully hardened by an oil quench, we use in our steel substantial amounts of the elements manganese, chromium, and molybdenum, which are effective in providing good hardenability in steel.

We limit the manganese to a maximum of about 1% because manganese strongly retards the transformation of austenite and thus a high manganese content makes annealing difficult, and furthermore depresses the Mf temperature causing austenite to be retained at room temperature. We limit manganese, therefore, to 0.30 to 1%, and preferably 0.40 to 0.70%.

Chromium and molybdenum are beneficial not only for increasing hardenability but also for causing resistance to softening during tempering. Our investigations have established that steels containing molybdenum as high as 4% are not appreciably more resistant to tempering than steel containing about 2 to 3% molybdenum, as may be seen from the data in Table I below.

TABLE I

Effect of Mo *on Hardness of Steel After Tempering*

[All samples heated to 1950° F.—30 min., oil quenched, and tempered 2 hours at temperatures indicated]

Bar	Composition percent, bal. Fe						Rockwell "C" hardness				
	C	Mn	Si	Cr	V	Mo	As quenched	As tempered at ° F.			
								950	1,000	1,050	1,100
6737--	.38	.47	1.0	3.4	.29	2.3	59	57	56	55	53
6945--	.41	.62	1.0	3.3	.32	2.3	61	58	57	55	54
6736--	.38	.49	1.0	3.3	.28	2.8	56	58	56	55	53
6944--	.41	.62	1.0	3.2	.32	2.8	62	60	59	57	55
6943--	.38	.69	1.0	3.5	.28	3.2	60	60	59	56	55
6526--	.45	.44	1.0	3.1	.36	3.3	63	60	58	57	56
6529--	.40	.60	1.0	3.1	.34	4.0	59	58	57	56	54

We accordingly limit molybdenum to 2 to 3%, preferably 2.2 to 2.8%.

We limit chromium to about 4% on the high side because larger amounts of chromium tend to decrease resistance to softening during tempering. This is shown by the data in Table II below.

TABLE II

Effect of Cr *on Hardness of Steel After Tempering*

[All samples heated to 1950° F.—oil quenched, and tempered 2 hours at temperatures indicated]

Bar	Composition percent, bal. Fe							Rockwell "C" hardness					
	C	Mn	Si	Ni	Cr	V	Mo	As quenched	As tempered at ° F.				
									900	950	1,000	1,050	1,100
6455--	.38	.6	1.0	1.9	1.8	.25	3.8	58	56	57	56	56	53
6456--	.37	.6	0.9	2.0	3.7	.34	3.9	60	59	60	59	57	52
6457--	.36	.6	0.9	2.0	5.2	.24	3.9	60	60	60	58	54	47

We accordingly limit chromium to 2.5 to 4%, and preferably 3.0 to 3.5%.

Since, as has been shown by Allten and Payson, Trans. ASM, vol. 45, 1953, page 498, silicon retards softening by tempering in the range of about 400 to 700° F., we prefer to keep silicon in the range of about 0.5 to 2%, and preferably 0.8 to 1.5%.

We have found that vanadium is very effective in preventing softening during tempering of the steels of this invention in the range 900° to 1100° F., and we, therefore, use a minimum of about 0.20% in our steel, and a maximum of about 0.5% vanadium, the preferred range being about 0.25 to 0.4% vanadium.

Although tungsten is effective in preventing softening during tempering in the range 900° to 1100° F., it is much less effective in this respect than vanadium. We, therefore, do not include tungsten in our steel, except to the extent that it may be present as a residual element.

It has frequently been stated that nickel in amounts up to about 5% imparts toughness to steel heat treated to high strength levels. However, as will be shown below, we have found that our steel containing no more than residual amounts of nickel, is as tough at high strength levels as steel containing as much as 2% nickel. Since nickel is in short supply, we do not specify nickel as an essential constituent in our steel.

The broad and preferred ranges for the steel of our invention are:

	Broad	Preferred
Carbon	.35 to .45	.38 to .43.
Manganese	.30 to 1.0	.40 to .70.
Silicon	.20 to 2.0	.80 to 1.50.
Nickel	Less than 0.5	None.
Chromium	2.5 to 4.0	3.0 to 3.5.
Vanadium	.10 to 0.50	0.25 to 0.40.
Molybdenum	2.0 to 3.0	2.2 to 2.8.

NOTE.—Balance iron with usual impurities.

In the accompanying drawings:

FIG. 1 is a graphical comparison of the resistance to tempering of a typical steel according to the present invention versus various commercial grades. In this showing tempering temperatures are plotted as abscissae against Rockwell "C" hardness values plotted as ordinates, and as obtained for the various steels over the range of tempering temperatures shown. The compositions of the steels compared are given in the drawing.

FIG. 2 is a graphical comparison of the tensile strength of a typical steel according to the invention versus various commercial grades over the temperature range extending from room temperature up to about 1000° F., temperatures being plotted as abscissae versus corresponding tensile strength values plotted as ordinates. In this figure also the compositions of the steels compared are shown in the drawing.

FIGURE 1 shows that over the tempering range of 1000° to 1200° F., the steel of this invention has a better hardness than any of the conventional steels tested with the exception of the cobalt-bearing steel B47, and this steel is inferior to the steel of the invention at temperatures up to about 1100° F.

FIGURE 2 shows that the steel of this invention has much higher tensile strength at all temperatures up to 1000° F. than any of the commercial grades of high strength steels shown.

In the following Table III are shown tensile data over the range extending from room temperature up to 1100° F. for steels of this invention compared with two conventional hot work steels, one being a relatively expensive steel containing about 2% nickel and 4% molybdenum, and the other being an average cost steel, the test data being based on measurements made in the longitudinal direction of the test bars.

TABLE III

Tensile Properties at Temperatures up to 1,100° F. of Steels of This Invention Compared With Conventional Hot Work Steels

[All samples heated to 1,950° F., oil quenched. Those tested at 1,000° F. and below were tempered 2 hours at 1,000° F.; those tested at 1,100° F. were tempered 2 hours at 1,100° F.]

	Steels of this invention [a]				Conventional steels [a]	
Bar	6737	6945	6736	6944	6942	5332
Room temp.:						
Tensile, p.s.i.	295,000	313,000	310,000	313,000	328,000	284,000
Yield,[1] p.s.i.	228,000	238,000	247,000	248,000	232,000	218,000
Elong.,[2] percent	8.0	7.0	9.0	8.0	7.5	11.5
Red. area, percent	38.5	31.0	34.0	36.0	28.0	49.5
800° F.:						
Tensile, p.s.i.	256,000	259,000	262,000	264,000	270,000	243,000
Yield,[1] p.s.i.	187,000	202,000	201,000	220,000	212,000	181,000
Elong.,[2] percent	11.0	10.5	8.5	9.0	9.5	11.5
Red. area, percent	48.5	48.0	41.0	39.0	33.0	50.0
1000° F.:						
Tensile, p.s.i.	228,000	225,000	228,000	235,000	233,000	214,000
Yield,[1] p.s.i.	161,000	167,000	183,000	198,000	163,000	161,000
Elong.,[2] percent	11.0	11.0	10.0	11.0	8.5	10.5
Red. area, percent	42.5	46.0	45.0	36.0	22.0	45.5
1100° F.:						
Tensile, p.s.i.	155,000	170,000	168,000	182,000	118,000	144,000
Yield,[1] p.s.i.	142,000	121,000	136,000	151,000	91,000	102,000
Elong.,[2] percent	10.5	10.0	12.0	11.5	13.0	15.0
Red. area, percent	41.5	36.0	48.5	39.0	61.0	59.0

[a] Of the above, bars 6737, 6945, 6736 and 6944 represent this invention; their analyses are shown in Table I. The other two are conventional hot work steels which analyze:

Type	Bar	C	Mn	Si	Ni	Cr	V	Mo	W
HIA	6942	.38	.79	.90	2.15	5.82	.32	3.85	----
Chro. Mow	5332	.33	.48	1.05	0.11	4.90	----	1.18	1.14

[1] 0.2% offset yield strength.
[2] Percent elongation in 2".

The above data show that the steel of this invention is about equal to the high-priced nickel-bearing steel at temperatures up to and including 1000° F., and is considerably stronger at 1100° F., and is generally superior to the average cost steel at all temperatures and particularly at 1100° F.

For a comparison of notch-sensitivity values at 1000° F. of the steels of this invention as compared to the conventional steels of Table III, above, 0.357 in. diameter tensile test pieces machined with a circumferential notch 0.250 in. diameter at the root of the notch, and with a notch radius of 0.016 in., were tested. The data are shown in Table IV below. It has been established that the greater the ratio of notched bar to smooth bar tensile strength, the less the notch-sensitivity of the steel (see paper by Sachs, Lubahn, and Ebert, Trans. ASM, vol. 33, 1944, page 340).

TABLE IV

Comparison of Smooth and Notch Tensile Strength at 1000° F.

[Specimens heated at 1950° F., oil quenched, and tempered 1000° F.—2 hours]

Bar	Average tensile strength smooth bar, p.s.i.	Average tensile strength notched bar, p.s.i.	Ratio, notched to smooth
6737	228,000	340,000	1.49
6945	225,000	340,000	1.51
6736	228,000	340,000	1.49
6944	235,000	333,000	1.42
6942 [1]	233,000	306,000	1.31
5332 [1]	214,000	325,000	1.52

[1] Conventional steels.

These data show that the steel of this invention is less notch-sensitive than the more expensive nickel-bearing steel Bar 6942 and only slightly more notch-sensitive than the average cost steel, Bar 5332.

Further data on relative toughness of the steels of the invention are given in Table V below.

TABLE V

V-Notch Charpy Tests on Steels Heat Treated to "C" 55 to 59 Rockwell

Steel	Rock. C	V-notch charpy, ft.-lb. at—		
		80° F.	300° F.	800° F.
This invention	58	11	15	16
Ni-Steel, bar 6942, Table III	59	9	12	13
Bar 5332 of Table III	56	12	22	22
B47 of Figure 1	55	2	3	9
Peerless A of Figure 1	55	3	3	14

Thus it is evident that the steel of this invention is tougher than the nickel-bearing steel, and considerably tougher than the higher alloy steels designated B47 and Peerless A.

What is claimed is:

1. An alloy steel consisting essentially of about: 0.35 to 0.45% carbon, 0.3 to 1% manganese, 0.5 to 2% silicon, 2.5 to 4% chromium, 2 to 3% molybdenum, 0.1 to 0.5% vanadium, under 0.5% of nickel, balance substantially iron, characterized by a tensile strength in the quenched and tempered condition of at least 290,000 p.s.i. at room temperature and at least 150,000 p.s.i. at 1100° F., and by an accompanying reduction of area of at least 28% at room and elevated temperatures up to 1100° F.

2. An alloy steel consisting essentially of about: 0.38 to 0.43% carbon, 0.4 to 0.7% manganese, 0.8 to 1.5% silicon, 3 to 3.5% chromium, 2.2 to 2.8% molybdenum, 0.25 to 0.4% vanadium, balance iron except for impurities within commercial tolerances, characterized by a tensile strength in the quenched and tempered condition of at least 290,000 p.s.i. at room temperature and at least 150,000 p.s.i. at 1100° F., and by an accompanying reduction of area of at least 28% at room and elevated temperatures up to 1100° F.

3. A steel alloy consisting essentially of 0.35% to 0.45% carbon, 0.30% to 0.70% manganese, 0.75% to 1.50% silicon, 3.00% to 4.00% chromium, 2.00% to 2.50% molybdenum, 0.25% to 0.50% vanadium, and the balance substantially all iron.

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