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LOW ALLOY STEEL HAVING HIGH HARDNESS
AT ELEVATED TEMPERATURES

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This invention pertains to steels of relatively low alloy content which are hardenable by quenching and which undergo secondary hardening upon subsequent tempering. More specifically, it pertains to alloy steels capable of achieving maximum as-quenched and tempered hardness with the ability to resist softening over relatively long periods of time when subjected to elevated temperatures.

The steady rise in operating temperatures of bearings, extrusion dies, turbine components, cutting tools and the like has created the demand for steels having superior physical and mechanical properties at elevated temperatures. Attempts have been made to use the known hot work and high speed tool steels for such applications; however, these attempts have met with only partial success and the steels having the better high temperature properties are the more expensive high alloy grades.

We have found that a steel alloy may be prepared which has a relatively low alloy content and which at the same time has good resistance to softening during very long exposures at temperatures at or above 1000° F. The steel of the invention contains as essential constituents, in addition to iron and carbon, chromium, vanadium, tungsten and molybdenum and may also contain cobalt. The broad composition limits are 1.0 to 1.25% carbon, 2.0 to 6.0% chromium, 1.75 to 2.5% vanadium, 4.0 to 10% tungsten, 2.0 to 5.0% molybdenum and 0 to under 9% cobalt.

As will become apparent from the following detailed description, the superior properties of the invention are due to the phenomenon known as secondary hardening, sometimes called "red hardness." In this process the steel is first austenitized and hardened by cooling in oil or in air and is thereafter tempered during which time the hardness first falls and then rises. The austenitizing treatment involves heating at a relatively high temperature to dissolve the alloying elements which are required to produce the secondary hardening. The second treatment involves a reheating at some lower temperature at which the dissolved alloying elements are precipitated in the form of very finely dispersed compounds, called carbides, to pro-

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duce hardening. The austenitizing treatment employed prior to the cooling for hardening serves a dual purpose. Not only does it dissolve carbon in the austenite so that the austenite will subsequently transform to a hard, high carbon martensite, but it also dissolves tungsten, molybdenum and vanadium to make these elements available for the secondary hardening reaction during tempering. The dissolved elements remain in solid solution during the austenite to martensite transformation and during the early stages of tempering. Subsequently the alloying elements combine with the carbon in the steel and form carbides which are precipitated in the matrix of the tempered martensite. This precipitation of fine alloy carbides accounts for secondary hardening or red hardness.

The elements in the steel responsible for producing secondary hardening, in addition to carbon, are tungsten, molybdenum and vanadium. These elements combine with carbon in the heat treatment to form the carbides Mo₃C, W₂C, (Fe,Mo,W)₆C and VC. It is these carbides which produce the secondary hardening effect. Chromium, on the other hand, forms the carbides Cr₇C₃ and Cr₂₃C₆. At the austenitizing temperature nearly all of the chromium carbides go into solution in austenite, and the total carbon from this carbide is, therefore, dissolved in the martensite formed during the subsequent quenching of the steel. Chromium also helps to retard tempering of the steel in that it delays the precipitation of the carbides in tempering. However, it does not impart secondary hardness in the steel itself. The element cobalt is not a strong carbide forming element and is added to the steel to retard softening, particularly in the later stages of tempering. Cobalt tends to decrease the amount of retained austenite in the steel and is effective in minimizing the size change of the steel during long time exposures at elevated temperatures.

In accordance with the invention, the carbon content of the alloy is balanced with the other elements present whereby a maximum amount of secondary hardening carbides are formed during tempering while a minimum amount of carbon is left to cause the retention of austenite after quenching. Thus, an adequate amount of carbon is required for the formation of a maximum amount of the alloy carbides in order to produce secondary hardening whereby the steel will retain its hardness at high temperatures over long periods of time.

A comparison of the resistance to tempering of the steels of the present invention (designated by the WB numbers) with that of commercial tool steels (designated by the T and M numbers) is shown in Table I.

TABLE I

Steel Designation	C	Cr	V	W	Mo	Co	Annealed ^a	As Quenched ^b	Rockwell "C" Hardness															
									Tempering at 1000° F.				Tempering at 1050° F.				Tempering at 1100° F.				Tempering at 1150° F.			
									2 hr.	4 hr.	8 hr.	16 hr.	2 hr.	4 hr.	8 hr.	16 hr.	2 hr.	4 hr.	8 hr.	16 hr.	2 hr.	4 hr.	8 hr.	16 hr.
WB18-----	1.07	4.6	2.1	4.8	4.5	-----	18	60	65	68	68	68	67	68	67	65	67	67	67	65	67	65	64	60
WB39-----	1.1	4.6	1.9	4.8	4.8	5.0	22	64	67	68	68	68	67	68	67	67	66	67	65	65	65	65	64	60
WB44-----	1.08	2.7	1.9	4.7	4.6	5.2	19	65	68	68	68	68	67	67	67	67	67	67	66	65	67	65	64	60
WB49-----	1.09	4.2	1.9	6.7	3.7	5.2	23	65	67	68	68	68	68	68	68	68	67	68	67	66	67	66	65	59
T-1-----	0.67	3.9	1.4	18.2	-----	-----	-----	-----	66	67	66	65	66	66	65	65	65	64	64	63	64	63	60	58
M-2-----	0.79	3.8	1.8	6.4	4.9	-----	-----	-----	65	66	67	64	66	65	64	64	64	64	63	61	63	61	60	58
M-1-----	0.76	3.7	1.2	1.3	8.5	-----	-----	-----	66	67	67	66	66	66	65	64	63	63	62	63	62	61	59	
T-6-----	0.80	4.5	1.5	20.0	-----	12.0	-----	-----	66	-----	-----	-----	-----	-----	-----	65	66	65	64	65	64	62	62	60

^a The steels were subjected to the following spheroidizing anneal:
1. Austenitized for 2 hours at 1600° F.
2. Furnace-cooled to 1450° F.
3. Cooled from 1450 to 1200° F. at 25° F. per hour.
4. Air-cooled from 1200° F. to room temperature.
^b The steels were austenitized at the following temperatures:
WB18-2275° F. T-1-2350° F.
WB39-2275° F. M-2-2250° F.
WB44-2225° F. M-1-2200° F.
WB49-2225° F. T-6-2375° F.

In all cases, the steels shown in Table I were hardened by being austenitized, quenched, and then tempered at the respective temperatures and times shown. Hardness readings were taken after the steels were cooled to room temperature after tempering. It will be noted from Table I that the hardnesses of the steels of this invention are very stable for different tempering times at 1000° F., 1050° F., and 1100° F. A slight drop in hardness is observed in the steels only after tempering for 8 or 16 hours at 1150° F. The steels WB18, WB39, WB44 and WB49, for example, all show Rockwell "C" hardness values of 67 to 68 after tempering for 4 hours at 1100° F. This hardness is higher than that obtainable with any commercial tool steel quenched and tempered in the same manner. As a matter of fact, almost all readings taken from steels of the present invention are higher than those taken from known tool steels which were heat treated under corresponding conditions. It will also be observed that the high hardness and unusual resistance to tempering of the steel compositions of this invention are achieved with a relatively low aggregate of chromium, vanadium, tungsten, and molybdenum which are carbide forming elements. That is, the total content of carbide forming elements for WB49, for example, is 16.5% and that for WB44 is 13.9%. In the known tool steel T-6, having the best hardness readings, however, the corresponding total carbide forming alloy aggregate is 26%.

The hardness retention of the steels of the present invention as compared with known tool steels is shown in Table II, where hardness retention parameters for various values of Rockwell hardness, Rc, are given.

TABLE II

[1.1C, 1.9V Base]

Steel	Cr	W	Mo	Co	Parameter for Rc		
					66	63	60
WB49	4.2	6.7	3.7	5.2	33,150	34,150	34,650
WB44	2.7	4.7	4.6	5.2	33,000	34,100	34,750
WB39	4.6	4.8	4.8	5.0	33,000	34,000	34,500
WB37	4.7	4.7	4.7		32,950	34,250	34,650
WB36	2.5	4.6	4.6		32,800	34,150	34,800
M-2					30,500	32,400	33,600
M-1					31,300	32,400	34,000

The parameter used in Table II is equal to:

$T(20+\log t)$

steel which has the same hardness value with a lower parameter. It is evident from Table II that the steels of the present invention (i.e., WB49, WB44, WB39, WB37 and WB36) maintain a given Rockwell hardness to higher parameters than the known commercial tool steels M-2 and M-1, the compositions of which are given in Table I. Specifically, the steels of the present invention have a hardness value of Rockwell "C" 66 for parameters ranging between 32,800 and 33,150; whereas, the known tool steels M-1 and M-2 have this hardness for a parameter value no higher than 31,300. The same comparison exists for Rockwell "C" hardnesses of 63 and 60. Thus, if each of the steels shown in Table II is heated at 800° F. and 1000° F. for 1,500 hours, respectively, those of the present invention will have a higher hardness at the completion of this treatment than the commercial tool steels M-1 and M-2. This effect is illustrated in Table III where hardness readings were taken at room temperature.

TABLE III

Steel Designation	Rockwell "C" Hardness		
	As Heat Treated ¹	After 1,000 hours at 800° F.	After 500 hours at 1,000° F.
WB49	69	69	66
WB44	68	68	65
WB39	69	69	66
WB37	68		66
WB36	67		65
M-2	66	65	61
M-1	66	66	61

¹The steels were austenitized at temperatures shown in Table I and were subsequently tempered for 2 plus 2 hours at 1050° F.

Table IV shows the effects of the chemical formulation of the steel upon the hardness retention during tempering. All steels shown in this table were austenitized at about 2200° F., and the hardness readings were taken at room temperature.

The steels WB20, WB22, and WB21 represent the effect of raising the carbon content from 0.84% to 1.08% while otherwise maintaining the same alloy balance in the cobalt-free steels. It is seen that for these steels the temper resistance increases with carbon content at all tempering time-temperature combinations. Similarly, the

TABLE IV

Steel Designation	C	Cr	V	W	Mo	Co	Annealed	As Quenched	Rockwell "C" Hardness															
									Tempering at 1000° F.				Tempering at 1050° F.				Tempering at 1100° F.				Tempering at 1150° F.			
									2 hr.	4 hr.	8 hr.	16 hr.	2 hr.	4 hr.	8 hr.	16 hr.	2 hr.	4 hr.	8 hr.	16 hr.	2 hr.	4 hr.	8 hr.	16 hr.
WB20	0.84	2.4	2.1	4.7	4.4		12	66	67	67	66	66	65	64	64	63	64	64	63	62	63	62	58	56
WB22	0.96	2.6	2.1	4.7	4.5		18	65	67	67	67	67	67	67	66	66	66	66	65	64	67	64	60	58
WB21	1.08	2.4	1.9	4.7	4.5		19	63	66	67	68	68	67	68	67	67	66	66	66	65	66	65	62	61
WB35	1.0	.07	1.9	4.5	4.6		18	68	64	64	66	66	65	66	66	66	66	65	65	64	65	64	63	59
WB36	1.1	2.5	2.0	4.6	4.6		18	65	66	66	68	68	67	67	67	67	66	66	65	66	65	64	62	62
WB37	1.11	4.7	1.9	4.7	4.7		21	55	63	65	68	68	66	68	68	68	68	66	66	66	66	63	65	63
WB38	1.08	6.7	2.0	4.7	4.6		21	47	54	55	61	61	58	58	58	58	59	64	66	62	66	62	62	60
WB11	0.86	4.8	1.8	5.0	4.9		18	61	67	67	67	67	67	66	66	65	65	63	61	63	61	58	55	53
WB12	1.02	4.7	2.9	5.0	4.7		19	63	67	67	67	66	65	66	66	63	65	64	62	59	62	59	56	55
WB16	0.85	4.5	1.9	4.8	4.5		16	63	66	67	67	67	67	66	65	64	66	66	65	64	65	64	59	54
WB25	0.88	4.7	1.9	4.8	4.5	5.1	20	63	67	68	68	67	68	68	66	66	66	66	65	64	65	64	61	56
WB26	0.89	4.5	1.8	4.6	4.5	10.1	22	63	69	69	68	68	68	67	67	67	66	66	66	66	64	66	64	57
WB24	0.84	2.6	1.8	4.8	4.4	9.7	19	66	68	68	67	67	67	67	66	65	65	65	63	60	56	54	51	
WB39	1.1	4.6	1.9	4.8	4.8	5.0	22	64	67	68	68	68	67	68	67	67	66	67	65	65	65	65	65	62
WB44	1.08	2.7	1.9	4.7	4.6	5.2	19	65	68	68	68	68	67	67	67	67	67	67	66	65	66	65	64	62
WB49	1.09	4.2	1.9	6.7	3.7	5.2	23	65	68	67	68	68	68	68	68	68	68	67	68	66	66	66	65	62

where T is the absolute temperature and t is the time in hours. It will be noted that the parameter increases whenever the temperature or the time increases. Thus, a steel which has a given hardness value with a higher parameter will maintain a higher hardness after being heated to 1000° F., for example, for 1,000 hours, than a

effect of raising the carbon content in the cobalt-containing steels is seen by comparison of the temper resistance of steels WB25 and WB39, which contain, respectively, 0.88 and 1.1% carbon in an otherwise practically identical base having a cobalt content of about 5%. It will be noted that steel WB25 is highly inferior in respect of

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temper resistance to steel WB39, the latter having a higher hardness at all tempering temperatures than does the former. At the rigorous tempering conditions of 16 hours at 1150° F., steel WB39 maintains a hardness of Rc 62, whereas, under the same conditions, steel WB25 has a hardness of only Rc 56. Steel WB25 is quite analogous to common prior art steel AISI M2-5 having an analysis of 0.8% carbon, 4.0% chromium, 2.0% vanadium, 6.0% tungsten, 5.0% molybdenum and 5% cobalt. The superiority of the inventive steels, illustrated by steel WB39, over such prior art steels, by reason of the increased carbon content of the inventive steels, is thus plainly evident. Thus, for both the cobalt and the cobalt-free steels, below approximately 1% carbon content, there is not enough carbon present to balance the carbide forming elements in the alloy and, consequently, a minimum carbon content of 1% is required to develop maximum hardness in the steels of the invention. When the carbon content is over about 1.25% in this type of steel, the balance no longer exists and an excessive amount of austenite is retained in the steel after it is austenitized and quenched. Therefore, the upper limit of the carbon content should be approximately 1.25%.

The steels WB35 to WB38 exemplify the variation of chromium content from 0.07% to 6.7% at a carbon level of 1 to 1.11%. Chromium up to 4.7% increases the hardness of the quenched and tempered steel over the whole range of tempering combinations. At the 6.7% chromium level, however, the proportion of retained austenite, as indicated by the lower hardness, is too great to be eliminated by multiple tempering cycles. Taking this factor into consideration, the upper limit of the chromium content should be at about 6.0% to prevent the retention of an appreciable amount of austenite with the accompanying reduction in hardness.

Steels WB11 and WB12 show the effect of the vanadium content on hardness. WB11 is at 1.8% vanadium while WB12 contains 2.9% vanadium. WB12 also has higher carbon content than WB11 which previously was shown to increase the temper resistance (see WB20, WB21 and WB22). In contrast, however, WB12 at the 3% vanadium level did not retain hardness at 1100° F. as effectively as WB11 at the 2% vanadium level. Therefore, for maximum hardness retention, the level of vanadium should be between 1.75 and 2.5%.

It is apparent from Table IV that the sum of the weight percentages of molybdenum plus one-half the weight percentage of tungsten should be between 6.5 and 7.5%.

In the group WB16, 24, 25, 26, about 5% and about 10% cobalt was added to the base composition containing about 0.85–0.90% carbon (WB24 differed in base composition only by reason of a somewhat lower chromium content, i.e., 2.6%). Comparing the temper resistance of the cobalt steels with that of WB16, which contained no cobalt, a hardness increase of 1 to 2 Rockwell "C" points is observed for the 5% cobalt steel over the entire range of tempering sequences, and, in the case of the higher cobalt steels, although a hardness higher than that of the cobalt-free steel is seen over the lower temperature portion of the tempering range, at the higher temperatures no advantage accrues and, in fact, lower hardnesses are obtained. Steels WB24 and WB26, containing, respectively 10.1 and 9.7% cobalt, were also found to have a lowered grain coarsening temperature. It is believed that this result is due to the tendency of cobalt to drive residual carbides into solution. Since grain growth is inhibited primarily by the "pinning" action of carbides in and adjacent the grain boundaries, any mechanism which decreases grain boundary carbides tends to enhance grain growth. Thus, in the case of a steel containing as high as 9.7% cobalt (WB24) or 10.1% cobalt (WB26), the carbide solubilizing force exerted by the cobalt is sufficiently great to result in appreciable increase in grain size. This effect of cobalt is

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particularly detrimental in the presence of other factors such as a high austenitizing temperature, which also promote grain growth. Furthermore, the higher cobalt contents did not produce a noticeable improvement in hardness retention at elevated temperatures and, indeed, as noted, hardness retention was somewhat less than that of the cobalt-free steel or the lower cobalt steel.

The effect of cobalt in the inventive steels upon life of tools made therefrom was also investigated, with results as given below:

TABLE V

Experimental Steel No.	C	Cr	V	W	Mo	Co
1-----	1.08	4.3	1.9	6.9	3.8	0
2-----	1.08	4.3	1.9	6.9	3.8	1.7
3-----	1.08	4.3	1.9	6.9	3.8	2.9
4-----	1.08	4.3	1.9	6.9	3.8	5.4
5-----	1.10	4.3	2.0	6.9	3.7	7.8

TABLE VI

Effect of cobalt upon tool life in cutting SAE 4340 stock of 52/55 Rc

Steel No.	Percent Co	Hardness, Rc.	Surface Speed, ft./min.	
			35	30
			Total Life, minutes ^b	
1-----	0	68.2	3.7(3)	7.0(1)
2-----	1.7	68.5	5.8(1)	-----
3-----	2.9	68.5	4.7(1)	10.2(1)
4-----	5.4	69.0	11.3(2)	17.2(2)
5-----	7.8	69.0	11.6(2)	21.5(2)
T-15 ^a	-----	-----	7.1(1)	11.9(2)

^a 1.5C, 4.0Cr, 5.0V, 12.0W, 5.0Co (prior art steel).

^b Numbers in parentheses show number of tests to get average value reported.

All specimens were austenitized at 2215° F. for 4 minutes, oil quenched and tempered 1050 (2+2 hours) + 1025° F.

The foregoing experimental results clearly show that addition of cobalt, in certain quantities, to the steels of the invention, has a beneficial effect upon the life of tools made therefrom. It is further evident that the superiority of the inventive steels over prior art low carbon (e.g., 0.8–0.9%), cobalt-containing steels, vis-a-vis cutting efficiency, is pronounced. Since, as shown hereinabove, the temper resistance of the high carbon, cobalt steels of the invention is clearly superior to that of the low carbon, cobalt steels of the prior art, it is apparent that the cutting efficiency of the former also is commensurately superior. Moreover, the addition of 5% cobalt to M-2 type steels, e.g., steel WB25, did not substantially improve the temper resistance thereof over that of the cobalt-free M-2 type steel WB20. Thus, the hardness of both steels falls to Rc 56 after tempering for 16 hours at 1150° F.

Since, therefore, the steels of the invention are highly useful, especially as cutting tools, when the cobalt content thereof is about 8% or thereabouts, and since, furthermore, increase of cobalt to about 9.7–10% tends to favor undesirable grain growth, the upper limit of cobalt is placed below about 9%.

Additionally, it has been found that steels having cobalt substantially in excess of about 9% have higher annealed hardnesses than do the lower cobalt steels. Thus a steel consisting of 1.10C, 1.9V, 4.3Cr, 6.8W, 3.8Mo, together with cobalt in an amount of 15.5%, was found to have an annealed hardness of 30 Rc. In contrast, the lower cobalt steels of the invention have annealed hardness less than 24/26 Rc, thereby being more suitable for ready machining.

The inventive steels, by reason of their low annealed hardnesses, are, as noted, readily machinable, despite the

high hardnesses to which they may be heat treated. For applications where machinability is a prime requisite, machinability of our steels may be still further enhanced by incorporation therein of a quantity of sulfur, say up to 0.3% and, preferably, up to about 0.2%.

Table VII compares the hot hardness at 600° F., 800° F., and 1000° F. of four steels of this invention with that of three commercial high speed tool steels. It is apparent that the drop in Rockwell "C" hardness over the given temperature interval is essentially the same for all seven steels.

TABLE VII

Comparison of hot hardness of four steels of this invention with that of three commercial high-speed tool steels

Designation	Austenitizing Temperature ¹	Rockwell "C" Hot Hardness			
		Room Temp.	600° F.	800° F.	1000° F.
WB18.....	2,225	68	63	60	58
WB39.....	2,225	69	64	60	59
WB44.....	2,225	69	65	61	58
WB49.....	2,225	68	64	61	59
T-1.....	2,350	66	60	57	55
M-2.....	2,250	66	60	58	56
M-1.....	2,200	66	60	57	55

¹ All steels were tempered 1050° F., 2+2 hrs.

It can be seen from Table VII that the attainable room temperature hardness is a good indication of the elevated temperature hardness of a specific steel analysis, and in this respect it will be noted that the steels of the present invention all have higher hardness at room temperature than those of the known tool steels, meaning that their hardness at elevated temperature also is greater.

Temper resistance is, of course, a vital factor in determining the suitability of a steel for construction of high speed tools since tool life depends, inter alia, upon the ability of the tool to maintain high hardness at the elevated temperatures generated during high speed cutting of workpieces of high hardnesses. The superiority of the steels of the invention over prior art high speed tool steels, when applied to such uses, is demonstrated by further comparative cutting tests with commonly used prior art high speed tool steels, the results of which tests are set forth hereinbelow in Tables IX-XIII.

TABLE VIII

Tool Steel Designation	Steel Composition, Weight Percent						
	C	Cr	V	W	Mo	Co	Fe
Steel WB49 (Modified)....	1.1	4.5	2.0	6.5	3.5	5.0	Bal.
AISI M-2.....	0.8	4.0	2.0	6.0	5.0	-----	Bal.
AISI M-3.....	1.0	4.0	2.7	6.0	5.0	-----	Bal.
AISI T-1.....	0.7	4.0	1.0	18.0	-----	-----	Bal.
AISI T-5.....	0.8	4.0	2.0	18.0	-----	8.0	Bal.
AISI T-6.....	0.8	4.5	1.5	20.0	-----	12.0	Bal.
AISI T-15.....	1.5	4.0	5.0	12.0	-----	5.0	Bal.

TABLE IX

Steel	Cutting Speed, Surface feet/min.	Average Tool Life, min.
AISI M-2.....	120	4.6
WB49 (Modified).....	120	9.3
AISI M-2.....	146.6	2.1
WB49 (Modified).....	146.6	2.7
AISI M-2.....	170.6	0.9
WB49 (Modified).....	170.6	2.4
AISI M-2.....	182.3	0.8
WB49 (Modified).....	182.3	1.3

In the above reported tests, the workpiece was SAE 4340 steel, having a hardness of Rb 92. Depth of cut was 0.034 inch, and feed rate was 0.010 inch/revolution. Two criteria were used to determine the end point of the test: (1) If tool wear was gradual, the point at which a sudden change in diameter could be observed was taken as the end point; (2) if, after a period of satisfactory cutting performance, the tool broke down rapidly, the instant of tool failure was taken as the end point.

It will be noted that the results reported above indicate superiority of the inventive steels, at every cutting speed tested, over the prior art high speed tool steel AISI M-2. This indication is further substantiated by the result of further tests comparing tool life of the inventive steels with additional prior art high speed steels under a variety of cutting conditions, including a wide spectrum of cutting stock. These results are given in Tables X-XIII below.

TABLE X

Single point lathe turning of AISI P-20 steel

Tool Steel Designation	Average Tool Life, Min. a. d					
	Roughing Cuts ^b			Finishing Cuts ^c		
	Average Cutting Speed, Surface feet/min.					
	30	35	40	43	70	80
	WB 49.....	57(3)	38(6)	24(3)	15(1)	47(2)
AISI T-15.....	36(2)	28(6)	17(4)	7(2)	58(2)	24(4)
AISI T-5.....	-----	13(1)	-----	-----	-----	-----
AISI T-6.....	-----	32(1)	-----	-----	-----	-----
AISI M-2.....	-----	-----	-----	-----	25(1)	13(2)
AISI T-1.....	-----	12(2)	-----	-----	-----	-----

^a Workpiece was AISI P-20 (0.3C, 0.75 Cr, 0.25 Mo, bal. Fe) of hardness BHN 300. Tool geometry: 3°, 6°, 10°, 10°, 0.030 inch nose radius.

^b Cutting Conditions: Depth of cut, 1/8 in.; Feed, 0.009 inch/rev.; Coolant, none.

^c Cutting Conditions: Depth of cut, 1/16 in.; Feed, 0.009 inch/rev.; Coolant, none.

^d Figures in parentheses indicates number of separate tests.

TABLE XI

Single point lathe turning of commercial stainless steels

Tool Steel Designation	AISI 410 Stainless (Rc 40) ^a			AISI 316 (Annealed)		AISI 303 (Annealed)			
	Average Tool Life in Minutes at Surface Cutting Speed in ft./min.*								
	60	70	75	40 ^b	50 ^c	60 ^b	65 ^b	75 ^c	80 ^c
WB 49-----	94(1)	47(1)	11(3)	66(2)	25.0(4)	23.3(1)	7.1(1)	24.5(2)	5.1(1)
AISI T-15---	58(2)	30(1)	5(3)	35(2)	18.0(4)	24.0(1)	9.2(1)	38.5	7.2(1)
AISI T-1---					12.8(2)			8.0	7.5(1)

*Figures in parentheses indicate number of cuts at each speed. Tool geometry: 3°, 6°, 10°, 10°, 0.030 inch nose radius.

^a Cutting Conditions: Depth of cut, 1/8 in.; Feed, 0.009 in./rev.; Coolant, None.

^b Cutting Conditions: Depth of cut, 1/8 in.; Feed, 0.015 in./rev.; Coolant, None.

^c Cutting Conditions: Depth of cut, 1/16 in.; Feed, 0.019 in./rev.; Coolant, None.

TABLE XII

Single point lathe turning of SAE 4340 steel

TEST NO. 1

Tool Steel Designation	Rc 22 a		Rc 32/35		Rc 41/45		Rc 48/52			Rc 52/55			
	Surface Cutting Speed, ft./min.*												
	100	70	50	55	60	65	30	45	20	25	31	35	
	Average Tool Life, minutes												
WB 49.....	-----	25	66.5	38.7	28.9	12.1	93.2	4.5	99.4	-----	45.1	35.6	
T-15.....	-----	35	80.8	38.1	19.7	7.3	73.2	2.8	35.6	-----	19.6	16.8	
M-15.....	-----	25	-----	-----	7.3	-----	-----	-----	9.0	-----	1.8	-----	
M-3.....	-----	-----	-----	-----	3.4	-----	-----	-----	Instantaneous Failure			-----	

TEST NO. 2

WB 49.....	26.5	-----	-----	35.0	10.0	-----	-----	116.0	34.5	-----	-----	-----
T-15.....	25.5	-----	-----	33.0	7.5	-----	-----	14.0	4.0	-----	-----	-----

*Tool geometry: 3°, 6°, 10°, 10°, 10°, 0.030 inch nose radius; ½ inch square cross section. ⅛ inch depth of cut; 0.009 inch/rev. feed; no coolant.

a Hardness of the workpiece (SAE 4340).

TABLE XIII

Single point lathe turning of difficult-to-machine alloys

Tool Steel Designation	Beta Titanium Alloy a, c		Waspalloy b, Rc 41 d		
	Average Tool Life in Minutes at Surface Cutting Speeds in ft./min.*				
	9.5	7.7	13	15	20
WB 49.....	25.3(3)	51.5(2)	62.9(1)	15.7(2)	5.8(1)
T-15.....	15.0(1)	15.0(1)	35.4(2)	15.0(2)	1.1(1)
T-5.....	6.0(2)	33.0(2)			
T-6.....			27.3(1)		
T-1.....			14.1(1)		

*Figures in parentheses indicate number of cuts at each speed. Tool geometry: 3°, 6°, 10°, 10°, 10°, 0.030 inch radius.

a 13% V, 11% Cr, 3Al bal. Ti.

b 0.07C, 0.07 Mn, 0.04 Si, 19.0 Cr, 56.0 Ni, 14.0 Co, 4.3 Mo, 3.0 Ti, 1.3 Al, 1.0 Fe.

c Titanium Alloy—rough turning of forgings with 2 in. sq. tools. Depth of cut, 0.500 in., feed 0.040 in.

d Waspalloy—light cuts; ⅛ in., depth; 0.009 in., feed; no coolant.

Inspection of the data of Tables IX–XIII will make readily apparent the versatility, as well as the generally over-all superiority, of the experimental steels, as exemplified by the Modified WB49 composition. Thus, these data show clearly that the steels of the invention are useful in the construction of cutting tools for a great variety of applications, e.g., the cutting of materials of a wide variety of hardnesses and over a wide range of cutting speeds. These data also show that the new steels are especially useful under the following circumstances: (1) in the cutting of usual low alloy materials, as SAE 4340, P-20 and 410, 316 and 303 stainless steels, especially where the hardness of these materials is increased to above Rc 30–40; (2) in heavy cuts of the usual, relatively low hardness workpiece materials, and (3) in cutting harder and/or more difficulty machinable materials, as the superalloys, titanium and its alloys, etc. Thus, the new steels are especially productive of enhanced tool life under the most rigorous conditions of cutting speed, workpiece hardness and heavy cuts. In this respect, our steels have no known equal.

It has been found, further, that a portion of the carbon content of the steels of the invention is substitutable by nitrogen, i.e., to the limit of nitrogen solubility in the steels, for example, up to about 0.10% nitrogen, under normal air melting of the steels. Such nitrogen-containing steels retain the advantages of the carbon-containing steels, as aforesaid, so long as the combined carbon and nitrogen content is within the required range, as afore-

said, for carbon alone, that is, from about 1.0 to about 1.25%. Thus comparative tool life tests were conducted with nitrogen-containing steels as follows:

TABLE XIV

Steel Designation	Steel Composition, Weight percent						
	C	N	(C+N)	Cr	V	W	Mo
59-303.....	0.83	0.03	0.86	4.1	1.8	6.4	5.1
59-304.....	0.98	0.03	1.01	4.1	2.0	6.3	5.2
60-423.....	1.04	0.08	1.12	4.2	2.0	6.4	5.0
59-305.....	1.10	0.03	1.13	4.1	2.0	6.2	5.2
60-422.....	1.09	0.08	1.17	4.1	1.9	6.3	5.0

In addition, the steels of Table XIV also contained, as normal steel-making additions and impurities, about 0.20 to 0.40% each of manganese and silicon and up to about 0.30% each of phosphorus and sulfur.

TABLE XV

Steel designation :	Average tool life, minutes a, b
59-303.....	14.4(2)
59-304.....	28.6(2)
60-423.....	37.6(2)
59-305.....	36.4(2)
60-422.....	41.5(2)

a Workpiece was AISI P20, containing 0.3C, 0.8Mn, 0.5Si, 0.8Cr, 0.25Mo, balance Fe, of hardness Rc 23/28. Cutting speed was 50 feet/minute and depth of cut was 0.100 inch. All tools had same geometry and dry cooling was utilized.

b Numerals in parentheses indicate number of separate tests. Tool life shown is average of all tests.

It will be seen from Table XV that steel 59-303, having a combined carbon plus nitrogen content of only 0.86%, gave a tool life only one-half that of the poorest of the steels of the invention, i.e., those having a combined carbon plus nitrogen content between 1.0 and 1.25%. It will also be noted that steels 59-305 and 60-423, containing substantially identical amounts of combined carbon plus nitrogen, also gave practically identical tool life, thus confirming the equality of effect of carbon and nitrogen (within the limits contemplated therefor).

The present invention thus provides a group of steels which retain a high hardness at elevated temperatures over relatively long periods of time; and it is apparent from the comparisons given above that the steel of the invention is far superior in this respect to the examples of the known tool steels cited.

Although the invention has been shown in connection

with a certain specific embodiment, it will be readily apparent to those skilled in the art that various changes in composition may be made to suit requirements without departure from the spirit and scope of the invention.

This application is a continuation-in-part of application Serial No. 755,856, filed August 19, 1958.

What is claimed is:

1. A forgeable alloy steel hardenable by quenching and secondary hardening and capable of retaining a hardness at room temperature of at least Rockwell "C" 64/66 after 500 hours exposure at 1000° F., and consisting essentially of about: 1 to 1.25% carbon, 2 to 6% chromium, 1.75 to 2.25% vanadium, 4 to 7% tungsten, 3 to 5% molybdenum, 0 to under 9% cobalt, and the balance substantially all iron.

2. An alloy steel consisting essentially of about: 1.0 to 1.25% carbon, up to 0.10% nitrogen, the combined carbon plus nitrogen being in the range of from 1.0 to 1.25%, 2 to 6% chromium, 1.75 to 2.5% vanadium, 4 to 7% tungsten, 3 to 5% molybdenum, 0 to under 9% cobalt, up to 0.3% sulfur, and the balance substantially all iron except for incidental impurities, said steel being characterized by being readily machinable in an annealed condition, by being hardenable by quenching from an austenitizing temperature, by undergoing secondary hardening to Rockwell "C" 67/69 upon tempering at a temperature between about 1000° F. and 1100° F., and by an enhanced hardness retention after prolonged exposure at elevated temperatures.

3. An alloy steel consisting essentially of about: 1.0 to 1.15% carbon, up to 0.10% nitrogen, the combined carbon plus nitrogen being in the range of from 1.0 to 1.15%, 2 to 6% chromium, 1.75 to 2.5% vanadium, 4 to 7% tungsten, 3 to 5% molybdenum, 0 to under 9% cobalt, and the balance substantially all iron, said steel being characterized by being readily machinable in an annealed condition, by being hardenable by quenching from an austenitizing temperature, by undergoing secondary hardening to Rockwell "C" 67/69 upon subsequent tempering at about 1000-1100° F., and by an ability to retain a hardness of at least about Rockwell "C" 64/66 after exposure for 500 hours at 1000° F.

4. A forgeable alloy steel hardenable by quenching and secondary hardening and capable of retaining a hardness at room temperature of Rockwell "C" 64/66 after 500 hours exposure at 1000° F. comprising about: 1 to 1.15% carbon, 3.75 to 4.25% chromium, 2 to 2.5% vanadium, 6.5 to 7% tungsten, 3.25 to 3.75% molybdenum, 5 to 6% cobalt and the remainder substantially all iron.

5. An alloy steel hardenable by quenching and second-

ary hardening and capable of retaining a hardness at room temperature of Rockwell "C" 67/69 after 1000 hours exposure at 800° F. comprising about: 1.05 to 1.25% carbon, 3.75 to 4.25% chromium, 2 to 2.5% vanadium, 6.5 to 7% tungsten, 3.25 to 3.75% molybdenum, 5 to 6% cobalt and the remainder substantially all iron.

6. An alloy steel capable of retaining high hardness at elevated temperatures over relatively long periods of time comprising about: 1.05 to 1.15% carbon, 2.25 to 4.5% chromium, 2 to 2.25% vanadium, 4.25 to 4.75% tungsten, 4.25 to 4.75% molybdenum, 5 to 6% cobalt, and the remainder substantially all iron with the usual impurities.

7. An alloy steel capable of retaining high hardness after exposure to temperatures above 1000° F. over relatively long periods of time comprising about: 1.05 to 1.25% carbon, 2 to 6% chromium, 1.75 to 2.25% vanadium, 4 to 7% tungsten, 3 to 5% molybdenum and 5.0 to 6.0% cobalt, the remainder being essentially all iron, the sum of the weight percentages of molybdenum and one-half the weight percentage of tungsten being between 6.5 and 7.5%.

8. A high speed cutting tool comprising a forgeable alloy steel hardenable by quenching from an austenitizing temperature and by subsequent secondary hardening upon reheating to a temperature between about 1000-1100° F. and characterized by enhanced tool life, said steel consisting essentially of about: 1 to 1.25% combined carbon plus nitrogen wherein the maximum nitrogen content is 0.1%, 2 to 6% chromium, 1.75 to 2.50% vanadium, 4 to 7% tungsten, 3 to 5% molybdenum, 0 to under 9% cobalt, up to 0.2% sulfur, and the balance substantially all iron.

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