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HIGH SPEED STEEL

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The present invention relates to an improved high speed steel.

More particularly the invention is concerned with the provision of a high speed steel adapted for the manufacture of metal cutting tools which will have greatly improved cutting qualities and durability over such tools now available in the art.

It is a principal object of the invention to provide a high speed steel appropriate for a metal cutting tool which will have enhanced qualities of hardness, toughness, and ability to withstand heat together with such qualities as abrasiveness, grindability and machinability required for a successful cutting tool.

It is a further object of the invention to provide an improved formulation of a high speed steel providing an alloy which is correctly balanced within a narrow range, which will produce machine cutting tools of greatly increased effectiveness as compared with tools produced of high speed steels of the prior art including toughness, resistance to wear and an ability to cut in both soft and medium-hard materials.

More specifically it is an object of the invention to provide a formulation of a high speed steel alloy in which the carbon combining elements of the alloy including tungsten, vanadium, molybdenum and chromium are included within closely defined ranges in the alloy, and in which the carbon content of the alloy is the total, within a tolerance of not more than ±.02%, of the amounts of carbon required to combine with each of said elements as determined with reference to especially established percentage carbon combining factors for each of said carbon combining elements.

High speed steel normally has as constituent elements therein iron as a matrix with additions of carbon, tungsten, vanadium, molybdenum, chromium, cobalt, manganese and silicon together with trace amounts of other elements including sulphur and phosphorus which have been combined in various proportions in an effort to provide a steel suitable for machine cutting tools. In general improved quality has been achieved by formulations enriched with massive additions of one or more of the principal alloying elements which would include carbon, tungsten, vanadium, molybdenum, cobalt and chromium. While high speed steels are available which have been so enriched with resulting increase in hardness, edge toughness and the like, such steels have been found to be extremely expensive and to lack balance of those qualities required for optimum use for machine cutting tools.

I have found upon investigation and by experimental results that a high speed steel, in which the several trace elements normally encountered are restricted to generally accepted small values, and in which the principal elements of the formulation including tungsten, vanadium, molybdenum, chromium and cobalt are present in moderate amounts determined in every case within critically narrow percentage ranges, and in which the amount of carbon in the formulation is critically determined in accordance with a newly provided scale of weight percentage carbon factors herein specifically set forth, provides a very substantially improved high speed steel adapted for the manufacture of machine cutting tools, which will out perform both general purpose and premium grade steels of the prior art for use in the manufacture of machine cutting tools. The carbon content of any particular formulation within the invention is critically determined as the sum of carbon percentages required by each of the carbon combining elements of the formulation, each said percentage being based in turn on a weight percentage carbon factor assigned to each of said elements. The experimentation has shown that variation of as much as .02% in the total percentage of carbon in the composition from the figure arrived at by use of my specified weight percentage carbon factors will cause a very rapid falling off in the quality of the machine cutting tools produced from steel with this formulation.

I have further found that variations from the weight percentage carbon factors tabulated below for the calculation of the percentage carbon in the formulation by as little as .01% particularly as adding up to a .02% or more variation from the theoretically correct figures here given will result in a very substantial loss of quality in the finished steel and in the machine cutting tools formed therefrom.

The weight percentage carbon factors which I have assigned to each of the several carbon combining elements of the carbon formulation are listed below in tabulated form as follows:

Table I

Element	Carbide Composition	Wt. Percent C combining with 1% Element
Chromium	$Cr_{23}C_6$	.055
Tungsten	W_2C	.033
Molybdenum	Mo_2C	.059
Vanadium	VC or V_4C_3	.200

An example of the manner in which this determination of carbon content is applied is given below in Table II for the H formula of Table IV—Chemical Analyses as follows:

Table II

	Factor	Alloy, Content
Cr	.055	3.98×.055=.2189
W	.033	1.76×.033=.0580
Mo	.059	8.48×.59 =.5003
V	.200	1.05×.200=.2100
Total Carbon		.9872

The rigid control of the carbon content of the high speed steel formula in accordance with my tabulation above set forth causes the several carbon combining elements to function more effectively in the formula to produce desired qualities of hardness, toughness, heat resistance, grindability and abrasiveness conducive to long life and efficiency in a machine cutting tool. For this reason a reassessment of the percentage requirement of

each of these elements in my improved high speed steel formula has become necessary. I have found that these elements must be included in accurately determined quantities in order to obtain a balanced formulation having in the highest degree those qualities best suited for the manufacture of machine cutting tools. The rigid limitation of the carbon content in accordance with my formulation will prevent the formation of saturated carbides with the alloy material with attendant undesirable effects which include hardness accompanied by a tendency of the steel to become brittle and to soften excessively in the presence of heat. My balanced formula will, however, include secondary iron carbides including Fe_3C which are not saturated by excessive alloy content, such carbides being valuable for the abrasive qualities which they produce in the steel to reduce wear of the cutting edge.

The preferred formulation in accordance with my invention, and the formulation which I have found to produce steel from which machine cutting tools of extraordinary efficiency can be made is tabulated in Table III as follows:

Table III

Element	Percentage by weight	Element	Percentage by weight
Mn	.15/.30	V	1.0
P	1.03	W	1.75
S	1.03	Mo	8.50
Si	.20/.40	Co	4.00
Ni	.05/.10	Cu	.05/.10
Cr	4.00	C	.98(±.02)

[1] Max.

In this formulation the inclusion of Mn, P, S, Si, Ni and Cu as trace elements may be regarded as normal.

In accordance with the invention six heats were melted to my experimental compositions including the preferred formulations in which changes were made in the percentages of the more important elements. The formulations of the six heats referred to are shown in the appended Table IV—Chemical Analyses as follows:

Table IV

CHEMICAL ANALYSES

Heat	Bar Code	C	Mn	P	S	Si	Ni	Cr	V	W	Mo	Co	Cu
1	E	1.07	.25	.012	.028	.23	.09	3.84	1.29	1.64	8.52	3.98	.06
2	M	1.05	.23	.013	.030	.32	.07	3.97	1.35	1.72	8.73	3.02	.06
3	H	.98	.29	.008	.030	.30	.09	3.98	1.05	1.76	8.48	3.98	.05
4	F	1.07	.26	.012	.025	.29	.06	4.10	1.25	1.86	8.66	.04	.05
5	K	1.05	.26	.012	.029	.22	.09	4.01	1.40	1.72	8.58	3.98	.07
6	R	1.05	.29	.011	.16	.23	.09	4.05	1.25	1.72	8.72	2.04	.07

Of the six heats melted, No. 3 having the bar code designation H conforms within a permissible margin of error to my preferred formulation given in Table IV. Heat No. 5, having bar code designation K, is similar to heat 3, bar code H, except that the percentage of vanadium has been increased to 1.40% and with a corresponding increase in the total carbon which is arrived at in accordance with the method outlined in Table I. Utilizing said formula, the carbon present should total 1.063%. The actual carbon in the heat at 1.05% is within the permissible range of error.

In heat 1, bar code E, the carbon content is 1.07% which is substantially above the permissible limit of 1.032%±.02% with a consequent decrease in efficiency as hereinafter pointed out. In each of the remaining heat 2, bar code M, heat 4, bar code F, and heat 6, bar code R, the carbon content is theoretically correct within the permissible margin of error, and all of the carbon combining elements are present within a reasonable range. Cobalt, however, has been sharply reduced in these latter heats varying in amount from 3.02% in heat 2 to .04% in heat F. It will be noted further that in heat 6, bar code

R, the sulphur content has been increased sharply from the .03 max. percent to .13%.

The quality of the steel produced in the six heats above described has been tested in the following manner:

Six 150 lb. air melt induction heats prepared according to the six chemical analyses of Table IV, were cast into ingots which were hammer logged to 2⅜" sq. x 2" equal length billets. After annealing and standard process heat conditioning, ingots according to each chemical analysis were made up into end mills of several different types, of which identical end mills from each heat were given the same identifying number.

Identical cutters were made up in accordance with standard procedure from each of the six heats. The cutters were ½" end mills of stock design having four cutting teeth. Those cutters listed in Part I of the tests tabulated in Table V below were tempered to a Rockwell hardness of 67 Rc. Those cutters listed in Part II of said Table V were tempered to a Rockwell hardness of 65 Rc. The #1 cutters had unground faces. The #5 cutters had ground faces.

Each cutter was subjected to a series of 18" cuts in identical test blocks, the cuts being ½" wide, .050" deep x 6⅞" feed at 600 r.p.m., with a limit factor of 150 lbs. ±5 on a strain gage.

Table V

PART I

Heat	Bar Code	Rc	Cutter, No.	Length of Cut, Inches
1	E	67	1	216
	E	67	5	234
2	M	67	1	162
	M	67	5	180
3	H	67	1	180
	H	67	5	180
4	F	67	1	198
	F	67	5	144
5	K	67	1	198
	K	67	5	234
6	R	67	1	180
	R	67	5	180

In each case, the cutter was continued in operation until too worn or broken for further use.

PART II

Heat	Bar Code	Rc	Cutter, No.	Length of Cut, Inches
1	E	65	1	162
	E	65	5	180
2	M	65	1	108
	M	65	5	90
3	H	65	1	126
	H	65	5	126
4	F	65	1	162
	F	65	5	144
5	K	65	1	144
	K	65	5	162
6	R	65	1	126
	R	65	5	144

In each case, the cutter was continued in operation until too worn or broken for further use.

Table V—Continued

PART III

Heat	Bar Code	Rc	Cutter, No.	Length of Cut, Inches
1	E	67	2	24
2	M	67	3	34
3	H	67	3	84
4	F	67	3	10
5	K	67	3	25
6	R	67	3	60

In each case the cutter broke.

PART IV

Heat	Bar Code	Rc	Cutter, No.	Length of Cut, Inches	
1	E	65	3	90	Finished in fair shape.
2	M	65	3	42	Cutter broke.
3	H	65	3	90	Finished in good shape.
4	F	65	3	74	Cutter broke.
5	K	65	3	90	Finished in good shape.
6	R	65	3	74	Cutter broke.

The H, E and K end mills finished the 90" cut, the H and K cutters in good condition. The R and F cutters each broke at 74" and the M cutter broke at 42".

From these tests it became immediately evident that the end mills made from steels having any one of my six chemical formulations were capable of exceptionally high performance not equalled in my experience by end mills made up from any available high speed steels in the prior art. End mills made up from the H formula were shown to have the highest degree of toughness and grindability. End mills made up from the K formula had nearly the same qualities. End mills made up from the E formula, while otherwise satisfactory, had a somewhat lower impact resistance.

A further series of tests were run upon end mills made up from E, H and K stock, the results of which are tabulated in Table VI.

All end mills were confined to stock design for a ½" diameter end mill. Hardness was 66 Rc.

The tests in Table VI, Parts I and II were made respectively with four-tooth and six-tooth cutters of ½" diameter upon a normalized block. The cut was ½" wide x .050" deep x 6⅞" feed at 600 r.p.m. Each end mill was kept in operation for the life of the tool.

Table VI

PART I

[½" four-tooth cutters Rc=66]

Heat	Bar Code	Cutter, No.	Length of Cut, Inches	Wear Land
1	E	1	576	.003
	E	2	396	.003
3	H	1	504	.004
	H	2	324	.004
5	K	1	414	.004
	K	2	342	.004

PART II

[½" six-tooth cutters Rc=66]

Heat	Bar Code	Cutter, No.	Length of Cut, Inches	Wear Land
1	E	1	432	.003
	E	2	342	.003
3	H	1	378	.004
	H	2	324	.003
5	K	1	360	.003
	K	2	270	.002

Additional tests (Parts III and IV) were made on a 200 Brinell block. A cut was made of ½" wide x ¼" deep x 7⅛" feed at 430 r.p.m. utilizing a four-tooth cutter.

PART III

[½" four-tooth cutter Rc=66]

Heat	Bar Code	Cutter, No.	Length of Cut, Inches	
1	E	3	7	Cutter broke.
3	H	3	90	Finished in good shape.
5	K	3	11	Cutter broke.

PART IV

[½" six-tooth cutter Rc=66]

Heat	Bar Code	Cutter, No.	Length of Cut, Inches	
1	E	4	90	Finished in good shape.
3	H	4	90	Do.
5	K	4	90	Do.

The test of Part V here recorded was made on normalized block. A cut was made ½" wide x ¼" deep x 7⅛" feed at 450 r.p.m.

PART V

[½" four-tooth cutter Rc=66]

Heat	Bar Code	Cutter, No.	Length of Cut, Inches	
1	E	4	90	Finished in good shape.
3	H	4	90	Do.
5	K	4	90	Do.

Samples of the steel obtained from each of the six heats designated as E, M, H, F, K and R, respectively, were tested to ascertain the degree to which each would resist deterioration from overheating as, for example, in resharpening or in cutting under heavy loads.

The response of samples from each of the several heats to a rigorous heat treatment was tested in the following manner:

Fifteen adjacent ½" thick discs were obtained from one (1) .510" diameter bar of each experimental analysis and heat treated as follows:

(Salt bath temperatures checked with immersed thermocouples.)

(1) Dummy load used each bath to simulate production heats.

(2) Preheated-salt furnace at 1500° F. for 15 minutes each test.

(3) Austenitized salt furnace:
- 18 samples 2125° F. 1 min. soak at temperature
- 18 samples 2150° F. 1 min. soak at temperature
- 18 samples 2170° F. 1 min. soak at temperature
- 18 samples 2190° F. 1 min. soak at temperature
- 18 samples 2210° F. 1 min. soak at temperature

  (A) Oil quench to room temperature.
  (B) Cross section surface ground and Rockwell C hardness quenched.
  (C) Cross section polished and Snyder-Graff grain size readings obtained.

(4) Tempered at 1000° F. 2+2 hours
Tempered at 1025° F. 2+2 hours
Tempered at 1050° F. 2+2 hours
  (A) Cross-sectioned surface ground and Rockwell C hardens after double temper.

(5) Retempered at 1000° F. 2 hours
Retempered at 1025° F. 2 hours
Retempered at 1050° F. 2 hours
  (A) Cross-sectioned surface ground and Rockwell C hardness after triple temper obtained.

The results of the tests above described are tabulated in Table VII as follows:

Table VII

Heat	Bar Code	Austenitizing Temperature, ° F.	Snyder-Graff, Grain Size	As Quench	Tempered 1,000° F.		Tempered 1,025° F.		Tempered 1,050° F.	
					2+2 Hrs.	2+2+2 Hrs.	2+2 Hrs.	2+2+2 Hrs.	2+2 Hrs.	2+2+2 Hrs.
1	E	2,125	18/12=15.2	C65.7	66.9	67.1	66.3	66.0	65.8	65.4
		2,150	17/11=13.6	C65.1	67.4	67.7	66.8	66.6	66.5	66.3
		2,170	16/11=12.9	64.6	67.5	67.9	67.1	66.8	66.9	66.5
		2,190	14/9 =12.3	63.8	67.6	68.1	67.4	67.2	67.2	66.7
		2,210	12/5 = 8.8	62.7	67.7	68.4	67.6	67.6	67.7	67.3
2	M	2,125	18/12=14.9	64.9	66.2	66.6	65.7	65.3	65.5	65.0
		2,150	17/11=13.4	64.4	66.4	67.2	66.4	65.9	66.3	65.9
		2,170	17/10=13.6	63.7	66.5	67.5	66.9	66.6	66.5	66.3
		2,190	17/10=13.3	63.2	66.6	67.7	67.2	66.9	67.0	66.5
		2,210	14/8 =10.7	61.7	66.3	67.9	67.8	67.3	67.5	67.3
3	H	2,125	19/12=15.3	65.4	67.0	67.1	66.1	65.7	65.6	65.3
		2,150	18/11=14.2	64.7	67.2	67.6	66.8	66.2	66.4	66.0
		2,070	17/12=14.0	64.2	67.5	67.8	67.2	66.9	66.7	66.4
		2,190	15/9 =12.2	63.5	67.4	68.2	67.4	67.2	67.0	66.8
		2,210	13/7 =10.7	62.2	67.3	68.4	68.0	67.2	67.5	67.4
4	F	2,125	18/12=15.2	64.0	65.5	67.7	66.1	65.6	65.4	65.3
		2,150	18/10=13.6	62.9	65.5	67.1	66.6	66.4	66.5	66.1
		2,170	16/8 =12.3	62.3	65.2	67.3	67.0	66.7	66.7	66.5
		2,190	14/8 =11.2	61.3	65.1	67.4	67.4	67.1	67.0	66.7
		2,210	14/7 =10.0	59.7	64.6	67.5	67.8	67.2	67.5	67.3
5	K	2,125	19/11=15.2	65.9	67.2	66.9	65.9	65.6	65.5	65.3
		2,150	18/11=14.1	65.3	67.5	67.5	66.7	66.4	66.0	65.7
		2,170	17/11=14.0	64.9	67.6	67.8	67.0	66.8	66.7	66.4
		2,190	16/10=13.1	64.4	67.7	68.0	67.4	67.1	66.9	66.5
		2,210	14/3 =10.7	63.4	67.8	68.3	67.6	67.5	67.3	66.8
6	R	2,125	18/11=14.9	65.7	66.7	67.1	66.1	65.7	65.3	65.0
		2,150	19/11=14.3	65.0	67.4	67.6	66.6	66.5	66.4	66.0
		2,170	17/11=13.6	64.6	67.4	67.7	67.1	66.8	66.6	66.4
		2,190	16/10=13.2	63.8	67.3	68.0	67.3	67.2	67.1	66.7
		2,210	14/7 =10.7	62.7	67.2	68.3	68.0	67.3	67.6	67.2

From an inspection of the results tabulated in Table VII it will be evident that both Snyder-Graff grain size and attainable hardness were remarkably similar from one to another of all six experimental formulas.

Snyder-Graff grain size, in all six analyses, showed only slight coarsening with increasing austenitizing temperatures through 2190° F. At 2210° F. the grain began to coarsen more rapidly although it was still at size 10 or above in five of the six analyses. Grain size was relatively fine throughout the experimental heats at 2190° F., the optimum austenitizing temperature, ranging from 11.3° to 13.3°.

Attainable hardness was also very good for all six experimental heats. A slight, but significant increase in tempered hardness with increasing austenitizing temperatures was experienced through the 2125/2210° F. austenitizing range. The high attainable hardness of these heats is illustrated by the high Rockwell of C67+, when obtained by austenitizing from 2190° F. and triple tempered at 1025° F.

The relatively high resistance to tempering of these experimental heats is shown by the slight decrease in hardness between the second and third tempers at 1025° F. and even at 1050° F. where the hardness would be expected at drop more sharply.

The results of the heat treatment tests above described in connection with Table VII disclose the fact that the steel produced by all six formulas of Table IV resisted to an extraordinary degree any tendency toward softening at elevated temperature.

The tests above tabulated for cutters made from steels having analyses 1 to 6 inclusive of Table IV demonstrate conclusively that a high speed steel melted in accordance with my balanced formulation has to an extraordinary degree those qualities required for the manufacutre of machine cutting tools of superior quality and efficiency. Cutters made from a steel in accordance with my preferred formulation of Table III identified as heat No. 3, bar code H in Table IV has produced cutters having qualities greatly improved over those obtainable with steels of the prior art. These cutters have a maximum hardness combined with outstanding qualities of toughness, grindability, abrasiveness and resistance to overheating which adapt such cutters for use with both hard and soft materials. Results obtained from the tests tabulated in Tables V and VI were substantially superior for all categories of use to those obtained from the finest grades of high speed steel commercially available including high speed steels especially enriched with alloying elements designed to provide a maximum efficiency for special purpose cutting. The six formulations set forth in Table IV were set up in order to test the effect of deviations from my preferred balanced formulation as defined in Table III and as defined in Table IV Analyses, heat No. 3, bar code H.

Cobalt has been found to be an essential ingredient within the limits of 3.5% to 4% to produce the standard of efficiency desired. The main effect of this alloy is to increase the red hardness, so that tools made from the alloyed steel may be used at increased speeds and with higher working temperatures at the cutting edge. Cutting efficiency is greatly increased. In the process of making steel, cobalt affects the melting point. Thus higher heats are permissible without a serious appreciable grain growth occuring. Also greater solutions of other alloys such as vanadium, chromium, tungsten, molybdenum and cobalt are taken in at the treating temperatures. There will also be a greater amount of retained Austenite left in the composition, with a greater amount of secondary hardness developed by additional tempering operation. I have also found that cobalt improves the grindability of the steel without generating heat at the cutting edge.

However, cobalt if used in amounts in excess of 4% tends to raise the austenitized temperature excessively and causes decarburization of the composition in all phases of treating temperatures above the critical temperature of said composition, and a consequent decrease in the toughness of the composition.

Chrominum is included in my composition within limits of 3.75% to 4.25%. The main effect of chromium is to cause hardness to penetrate deeper into the cast steel and when employed in sufficient quantity will permit the steel to be oil quenched, salt or lint quenched. As applied

specifically to machine tool cutters made from high speed steel, chromium contributes improved air hardening and wear resistance properties to the cutters. However, when used in amounts greatly in excess of the 4% specified in my balanced composition, chromium tends to combine with other elements in the matrix including carbon to from secondary carbides which cloud the operation of other alloying elements and their carbides in the composition.

It will be noted with respect to chemical formulations heat 2, bar code M; heat 4, bar code F; and heat 6, bar code R, that the cobalt content is substantially below the limits prescribed. The performance of cutters made from steels in accordance with these heats was less satisfactory than the performance of those made from the steels of heat 1, bar code E; heat 3, bar code H; and heat 5, bar code K.

Tungsten is included in my balanced composition in the preferred amount of 1.75%, but may be varied without serious loss of cutting tool quality between 1.5% and 2%. Tungsten forms a carbide of extreme hardness which is relatively unaffected by elevated temperatures providing a degree of red hardness which permits machine tool cutters made from steel having a substantial percentage of tungsten to operate at relatively high temperatures without deterioration. I have found, however, that tungsten when included in my balanced composition in amounts greatly in excess of the 1.75% specified causes the steel to become brittle with a resulting loss of impact strength and a resulting failure of tools made therefrom when placed under heavy load. Such increase of tungsten would require higher austenitizing temperatures which does coarsen the grain size, and adversely affects the arrangement of the other major elements in the solution of carbides within a matrix of iron.

Molybdenum is included in all six heats in amounts closely confined between 8.48% and 8.73%. Molybdenum is a lightweight metal having qualities similar to those found in tungsten and chromium, forming a double carbide when alloyed with carbon and iron. This metal tends to increase red hardness and wear resistance of cutting tools formed from the resulting steel. Like chromium, it increases hardness penetration, and produces a steel suitable for oil and air quenching.

It is believed that the percentages of tungsten and molybdenum employed in all six heats are within limits capable of producing a high speed steel of maximum efficiency for use in the manufacture of machine cutting tools. However, as the amount of molybdenum is increased beyond the range specified, saturated carbons are formed, and the composition becomes unbalanced with the loss of such important qualities as toughness, abrasiveness, grindability and the like. As the amount of molybdenum is increased the steel will become more subject to decarburization during forging and other mill operations, and during subsequent heat treatments with a consequent softening of the matrix.

The amount of vanadium included in the composition may be regarded as critical, varying between 1% and 1.50%. This metal has a very high affinity for carbon and in this connection is employed as a scavenger for carbon in the composition. The vanadium carbides are very hard, tend to increase the cutting efficiency along with resistance to wear, and prevent grain development at the austenitizing temperature. However, if the amount of vanadium in the composition is increased percentagewise beyond the 1.5% stated, the high percentage of vanadium carbides formed tends to reduce the grindability of the material.

Carbon is a critical ingredient and the principal hardening element in all steels. I have found that the carbon content of my balanced composition is extremely critical in determining the characteristics of a particular steel for use in the manufacture of machine cutting tools. The very high level of performance obtained with tools made from

steels having the analyses of heats 1 to 6, in Table IV, is attributable in large part to the extremely careful measurement of the carbon included in each composition in accordance with the percentage factors set forth in Table I. In this connection it may be noted that total carbon included in each of compositions 2 through 6, inclusive, is well within the .02% margin of error permissible. In heat 1, bar code E the carbon content is given as 1.07%, whereas, this content should theoretically be a 1.032%. Tests with cutters from steel having the bar code E were found to have substantially lower impact strength than those made from steels having bar code H and K. Inasmuch as the other elements of composition heat 1, bar code E, were well within permissible limits of variation from my preferred formula, heat 3, bar code H it is believed evident that the excess carbon content is responsible for the indicated loss of efficiency. It may be noted with respect to heat 4, bar code F, that the actual carbon content of 1.07% exceeds the theoretically correct carbon content by .022%, this excess of carbon taken in connection with the substantial elimination of cobalt in this formulation is believed responsible for the relatively poor showing of the cutters made from this steel (see Tables V and VI).

Silicon and manganese are present in my compositions in small quantities and are effective primarily in deoxidizing the steel in the final operation of melting. Manganese also combined with sulphur to form the relatively inoccuous nonmetallic inclusion manganese sulphide.

Sulphur in my balanced composition is kept below a maximum of .03%. It will be noted that cutters made from steel melted in accordance with heat 6, bar code R having .16% sulphur and also a relatively small amount of 2.04% cobalt, although otherwise within the limits prescribed, produced a substantially inferior performance in all categories of tests made.

The invention having been described, what is claimed is:

1. A high speed steel consisting essentially of about 3.98% chromium, about 1.76% tungsten, about 1.05% vanadium, about 8.48% molybdenum, about 3.98% cobalt, and about .98% carbon, and the balance iron with incidental impurities.

2. A high speed steel as claimed in claim **1** in which carbon is present as the sum of the carbon percentages required by the chromium, tungsten, molybdenum and vanadium present in accordance with carbon combining factors chosen, being the sum of .055× the percent chromium +.033× the percent tungsten, +.059× the percent molybdenum, +.2× the percent vanadium, the total carbon present being held within .02% of the total percentages arrived at, and the balance iron with incidental impurities.

3. A high speed tool steel consisting essentially of about .3% silicon, about .3% max. manganese, 0.3% max. sulphur, .03% max. phosphorus, .10% max. nickel, about 3.98% chromium, about 1.05% vanadium, about 1.76% tungsten, about 8.48% molybdenum, about 3.98% cobalt, .10% max. copper and about .98% carbon, the remainder iron with the residual impurities in usual amounts.

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