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LOW ALLOY HIGH SPEED STEEL

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This invention relates to low alloy high speed steels which are superior to those heretofore known. My steels are readily forgeable and, in fact, can be rolled directly from the ingot without prior forging. They are tough and abrasion resistant. These desirable properties are obtained by employing relatively narrow ranges of chromium, vanadium and molybdenum, the steels preferably but not necessarily also containing tungsten, and by the proper amount of carbon, which varies according to the amounts of these alloying elements as pointed out more particularly hereinafter.

In order to show more clearly the balanced composition of my steel, I work generally with atomic percentages of the elements rather than with the more commonly used weight percentages.

My high speed steels consist essentially of the elements within the following ranges but, in addition, the proportions of these elements must comply with Rules 1 and 2 described hereinafter:

	Weight Percent	Atomic Percent
Carbon	1.05–1.30	4.79–5.97.
Chromium	3.70–4.50	3.70–4.80.
Vanadium	3.70–4.50	3.97–4.86.
Tungsten	0–3.50 (preferred 2.20–3.50)	0–1.05. (preferred 0.66–1.05).
Molybdenum	2.20–6.00 (preferred 2.20–3.50)	1.25–3.42. (preferred 1.25–2.01).

The balance of the steel is substantially all iron.

Reference is now made to the following Tables I, II and III.

TABLE I

	Weight Percents					Atomic Percents				
	C	W	Cr	V	Mo	C	W	Cr	V	Mo
A	.72	18.00	4.00	1.00	-----	3.70	6.04	4.75	1.21	-----
B	.88	-----	4.10	1.82	4.25	4.02	-----	4.32	1.96	2.43
C	.82	1.50	4.00	2.00	8.50	3.86	.46	4.34	2.21	5.00
D	.83	6.00	4.00	2.00	5.00	3.97	1.87	4.42	2.25	2.99
E	1.15	6.00	4.00	3.00	6.00	5.45	1.86	4.38	3.35	3.56
F	.95	2.50	4.00	2.50	2.50	4.37	.75	4.24	2.71	1.43
G	1.00	3.00	4.00	3.00	3.00	4.57	.89	4.21	3.23	1.72
H	1.27	5.50	4.50	4.00	4.50	5.93	1.68	4.85	4.40	2.63
I	1.40	-----	4.10	4.15	4.25	6.26	-----	4.23	4.37	2.38
J	1.56	6.56	4.75	5.00	[1] 3.35	7.24	1.99	5.08	5.46	1.94
K	1.50	12.50	4.75	5.00	(1)	7.17	3.90	5.24	5.63	-----
L	1.09	2.40	3.90	4.20	2.50	4.97	.71	4.11	4.51	1.42
M	1.16	2.70	4.20	3.80	2.80	5.30	.81	4.43	4.09	1.60
N	1.09	2.20	3.70	3.50	2.20	4.96	.66	3.89	3.76	1.25
O	1.20	3.10	4.40	4.50	3.20	5.49	.92	4.65	4.85	1.83
P	1.09	3.10	4.40	3.50	3.20	5.01	.93	4.67	3.79	1.84
Q	1.20	2.20	3.70	4.50	2.20	5.44	.65	3.87	4.80	1.25
R	1.00	2.00	3.70	3.70	2.00	4.56	.60	3.89	3.97	1.14
S	1.13	2.55	4.05	4.00	2.65	5.16	.76	4.27	4.30	1.51
T	1.09	2.40	3.90	3.80	2.50	4.98	.71	4.11	4.09	1.43
U	1.16	2.70	4.20	4.20	2.80	5.30	.81	4.43	4.52	1.60
V	1.16	2.70	4.00	4.20	2.70	5.30	.81	4.21	4.51	1.54
W	1.20	3.00	4.00	4.30	3.00	5.49	.90	4.22	4.63	1.72
X	1.30	3.50	4.50	4.50	3.50	5.95	1.04	4.75	4.85	2.01
Y	1.05	2.20	3.70	3.70	2.20	4.79	.66	3.89	3.97	1.25
Z	1.13	-----	4.05	4.00	5.70	5.15	-----	4.26	4.28	3.25

[1] Contains 5% cobalt.

TABLE II

(1) Steel	(2) C_t	(3) C_v	(4) C_m	(5) $C_t-(C_v+C_m)$
A	3.70	1.21	1.80	.69
B	4.02	1.96	1.13	.93
C	3.86	2.21	1.63	.02
D	3.97	2.25	1.55	.17
E	5.45	3.35	1.63	.47
F	4.37	2.71	1.07	.59
G	4.57	3.23	1.14	.20
H	5.93	4.40	1.53	.00
I	6.26	4.37	1.10	.79
J	7.24	5.46	1.50	.28
K	7.17	5.63	1.52	.02
L	4.97	4.51	1.04	−.58
M	5.30	4.09	1.14	.07
N	4.96	3.76	.97	.23
O	5.49	4.85	1.23	−.59
P	5.01	3.79	1.24	−.02
Q	5.44	4.80	.96	−.32
R	4.56	3.97	.94	−.35
S	5.16	4.30	1.09	−.23
T	4.98	4.09	1.04	−.15
U	5.30	4.52	1.14	−.36
V	5.30	4.51	1.09	−.30
W	5.49	4.63	1.14	−.28
X	5.95	4.85	1.30	−.20
Y	4.79	3.97	.97	−.15
Z	5.15	4.28	1.25	−.38

C_t=total atomic percent carbon (from Table I).
C_v=total atomic percent vanadium (from Table I).
C_m=⅙ the sum of atomic percent of W+Cr+Mo (from Table I).

TABLE III

(1) Steel	(2) C_t	(3) C_v	(4) C_t-C_v	(5) $\frac{C_v}{C_t-C_v}$
A	3.70	1.21	2.49	.49
B	4.02	1.96	2.06	.95
C	3.86	2.21	1.65	1.34
D	3.97	2.25	1.72	1.31
E	5.45	3.35	2.10	1.60
F	4.37	2.71	1.66	1.63
G	4.57	3.23	1.34	2.41
H	5.93	4.40	1.53	2.88
I	6.26	4.37	1.89	2.31
J	7.24	5.46	1.78	3.07
K	7.17	5.63	1.54	3.66
L	4.97	4.51	.46	9.80
M	5.30	4.09	1.21	3.38
N	4.96	3.76	1.20	3.13
O	5.49	4.85	.64	7.58
P	5.01	3.79	1.22	3.11
Q	5.44	4.80	.64	7.50
R	4.56	3.97	.59	6.73
S	5.16	4.30	.86	5.00
T	4.98	4.09	.89	4.60
U	5.30	4.52	.78	5.79
V	5.30	4.51	.79	5.71
W	5.49	4.63	.86	5.38
X	5.95	4.85	1.10	4.41
Y	4.79	3.97	.82	4.84
Z	5.15	4.28	.87	4.92

Table I lists the steels A to Z in the first column. It shows the weight percents and the atomic percents of carbon and the alloying elements in many kinds of high speed steels. Steels A to K, inclusive, are examples of many commercially known high speed steels, all of which are outside the scope of my invention. Steels L to R, inclusive, are other steels outside the scope of my invention. Steels S to Z, inclusive, are steels according to my invention.

A satisfactory high speed steel should have the following properties.

First, it must be such that it can be readily forged and rolled. Many high speed steels now in use are so loaded with alloy in an effort to increase their abrasion resistance and cutting ability that they are difficult to forge and roll. My high speed steel not only can be readily forged but it can be rolled directly from the ingot.

Second, I desired a high speed steel that would possess greater toughness than other high speed steels so that tools made thereof would not break easily in use.

Third, I wanted a high speed steel that would possess good abrasion resistance and cutting ability.

Fourth, I wanted a steel that would be economical to make both from the standpoint of the cost of the ingredients of the steel mix and from the standpoint that less scrap would result in hot working the ingots into bars.

I have accomplished the first aim, i. e., to produce a steel that could be forged and rolled with relative ease, by keeping the alloy content of chromium, tungsten and molybdenum reasonably low.

The second aim, great toughness, has been accomplished by keeping the carbon content lower than has previously been thought possible considering the alloy content. I have discovered that, contrary to the teachings of others, the carbon should be kept at a lower amount than is actually needed to combine with all the carbide-forming elements. The relatively low alloy content of my steels also contributes to their toughness.

The third aim, abrasion resistance and cutting ability, have been attained by so alloying the steel that it possesses a preponderance of vanadium carbides as compared with other carbides. The vanadium carbides that I produce in such large quantities in my steel are much harder than the mixed carbides of tungsten, chromium and molybdenum found in high speed steels.

I will explain what I believe happens in the forming of carbides in my high speed steel, but I do not bind myself by such explanation.

The carbide-forming elements, tungsten, chromium and molybdenum, in high speed steel form mixed carbides expressed by the chemical formula $(W, Cr, Mo)_6C$. This means, in effect, that these three carbide-forming elements in the proportions in which they are present in the steel combine with 1/6 of their atomic percents of carbon to form a carbide. If the total of tungsten, chromium and molybdenum are taken together and considered as carbide-forming metals designated "M," the formula for the carbide may be expressed as M_6C. This means that 6 atoms of carbide-forming metal combine with 1 atom of carbon to form the carbide M_6C.

When a high speed steel is hardened by heating to a high temperature (about 2200–2400° F.) followed by fairly rapid cooling, its hardness may be found to be between Rockwell C 63–66. But if a microhardness tester is used, that can measure the hardness of the individual $(W, Cr, Mo)_6C$ particles, they will be found to be the equivalent of Rockwell C 77. It is considered that it is these harder carbide particles in the high speed steel that contribute to its abrasion resistance and cutting ability.

I believe that by a proper balancing of carbide-forming elements and carbon in my high speed steel, my vanadium goes to form a carbide that may be expressed chemically as VC. This means that 1 atom of vanadium will combine with 1 atom of carbon to form carbide. My steel possesses an abundance of these VC carbides, as may be seen by examining the microstructures. And the microhardness of these VC carbides is the equivalent of Rockwell C 84, which is intensely hard, and resists polishing by alundum; in fact, diamond dust has to be used to prepare metallographic samples or else these VC carbides stand up from the surface as rounded hills.

These VC type carbides are present in other high speed steels in varying amounts, but I have so balanced my alloy and carbon content that my high speed steel has more of them than any other steel with a similar vanadium content.

Table II lists the steels A to Z in the first column. The second column is headed C_t: this is the atomic percent of all the carbon in the steel. The third column is headed C_v: this is the carbon needed to combine with all the vanadium to form VC carbides, and since 1 atom of vanadium requires 1 atom of carbon to form this carbide, this C_v equals the atomic percentage of vanadium in the steel. The fourth column is headed C_m: this is the atomic percent of carbon required to form the M_6C type of carbide, or $(W, Cr, Mo)_6C$. It is evident that C_m equals one-sixth of the total of the atomic weights of tungsten, chromium and molybdenum. The fifth column is headed $C_t-(C_v+C_m)$, and expresses the excess or deficiency of carbon needed to form the various carbides.

From column 5 in Table II, it will be seen that many steels contain carbon in excess of that required to form carbides with the alloying metals. This excess carbon causes embrittlement of the steels. Some of the other steels contain a deficiency of carbon so that all of the carbide-forming elements cannot be used to advantage but are wasted. Other steels contain just a slight deficiency of carbon so that after the carbide-forming elements have been used without waste there will be positively no excess of carbon to embrittle the matrix of the steel.

In order that the steel be tough and have no excess of carbon to embrittle it, I have found that the steels must conform to the following rule:

Rule 1

$$C_t-(C_v+C_m)=-0.10 \text{ to } -0.40 \text{ atomic percent}$$

It is necessary that there be an actual deficiency of carbon as compared with the theoretical amount required for combining with all of the alloying elements. When there is a balance, just enough and no more than will from all the carbides, there is nevertheless an embrittling effect on the matrix of the steel.

Table II lists the steels A to Z in the first column. The second column is headed C_t: this is the atomic percentage of all the carbon in the steel. The third column is headed C_v: this is the carbon needed to combine with all the vanadium to form VC carbides, and since 1 atom of vanadium requires 1 atom of carbon to form this carbide, this C_v equals the atomic percentage of vanadium in the steel. The fourth column is headed C_t-C_v, and is the atomic percentage of carbon remaining after VC carbides have been formed. The fifth column is headed

$$\frac{C_v}{C_t-C_v}$$

and expresses the ratio between the carbon combined as VC carbides and the rest of the carbon.

Table III shows that in most of the commercially known steels A to K, the carbon combined with vanadium to form VC carbides is either less than or does not greatly preponderate over the carbon which is combined with the other alloying metals, or with iron to embrittle the matrix. I realize that in order to get as many VC carbides as possible, compared with the other carbides, I could eliminate all or a large proportion of the tungsten, chromium and molybdenum but the result would not be a "high speed steel"; a steel characterized by ability to retain high hardness at temperatures around 1050° F. after hardening from very high temperatures.

I have found that in order for the steel to contain as many of the very hard VC carbides as possible, in proportion to the $(W, Cr, Mo)_6C$ carbides, while still retaining the desirable characteristics of high speed steel, it must comply with Rule 2 as follows:

Rule 2

$$\frac{C_v}{C_t-C_v}=4 \text{ to } 6$$

This Rule 2 means that the ratio of carbon needed to form VC carbides to all the remaining carbon in the steel must be between 4 and 6.

When Rule 2 is followed, I get steels that contain a great many VC carbides in comparison with the softer carbides of the type $(W, Cr, Mo)_6C$, yet I make sure that there are enough of the softer carbides to give hardness to the matrix. High speed steels in the annealed condition have most of the carbides out of solution, but when they are heated for hardening, as the hardening temperature is raised and the time of holding increased

at the hardening temperature, more and more of the $(W, Cr, Mo)_6C$ carbides go into solid solution in the matrix to give it strength and hardness. However, in my steels the VC carbides, which are numerous and of large size, go into solution only with the greatest difficulty and at the maximum hardening temperature that can be used without excessive grain growth and with any reasonable time of holding at heat, the VC carbides do not go into solid solution in the matrix of my steels, but remain as numerous hard carbides.

Reference is now made to Rules 1 and 2 and the steels listed in Tables II and III.

Referring to Rule 1 and Table II, it is seen that none of the steels A to K complies with Rule 1. Steels A, B, E, F and I all have a large excess of carbon and are considerably less tough than steels S–Z, inclusive, according to the present invention. Steels D, G and J have a moderate excess of carbon. Steels D and J have high alloy contents and are not as tough as the steels of the present invention. Steels C, H and K, although they contain no theoretical excess of carbon, are highly alloyed and because of this are not as tough as the steels of the present invention.

Referring to Rule 2 and Table III, steels A and B contain so few VC carbides that they can hardly be found in the microstructure. In steels C, D, E and F a very few VC carbides can be seen in the microstructures. As we continue through steels G, H, I, J and K, more VC carbides are present in the microstructure, exactly as the ratio

$$\frac{C_v}{C_t - C_v}$$

increases in value. Steel K is very highly alloyed, is lacking in toughness, is very difficult to forge or roll, and is very expensive.

Steels S to Z, inclusive, according to the present invention, comply with Rule 1 and Rule 2. These steels are very tough. They have a relatively low alloy content and can be readily forged and, in fact, can be rolled directly from the ingot. They are inexpensive to manufacture. The number of VC carbides visible in their microstructures is very great; exceeding that of any other well known steel, and is the reason why my steels perform so well in cutting tests.

Steels F and G both contain too much carbon to comply with my Rule 1 and too few VC type carbides to comply with my Rule 2. Drills made of steels F and G have been tested in comparison with drills made of my steel S and it was found that the drills made from my steel had cutting life from 5 to 10 times that of the drills made from steels F or G.

Two drills made from my steel S drilled 123 and 155 holes respectively before failure, as compared to 33 holes for the same design drill made of steel C and used on the same test block. The average of 7 drilling tests showed that drills made from my steel S drilled 111 holes as compared with an average of 23 holes for drills made from steel C. These tests were made on a test block of chrome-nickel alloy, heat treated to 24 Rockwell C.

Steel I contains a great deal too much carbon to comply with my Rule 1 and to give optimum toughness. It does not contain enough VC type carbides to comply with my Rule 2 to give optimum abrasion resistance.

I have made steels L to R, inclusive, which are outside the scope of my invention, have tested them against steels S to Z, inclusive, which are within the scope of my invention. These tests were machining tests involving the use of single point cutting tools made from the various steels. They showed my steels S–Z to be considerably better than the other steels.

In steels L, O, Q and R the ratio

$$\frac{C_v}{C_t - C_v}$$

is too high to comply with my Rule 2. These steels contain too great a proportion of VC carbide compared with the amount of other carbides present to form a proper steel matrix. Thus these steels lack the property of red hardness and hardness at room temperature. It is not that there is any harm in having a large number of VC carbides in the steel but it is the paucity of the other kinds of carbides which results in a steel having an unsatisfactory matrix. In addition, steels L and O do not have sufficient carbon to comply with Rule 1.

In steels M, N and P the ratio of

$$\frac{C_v}{C_t - C_v}$$

is too low to comply with Rule 2 and accordingly these steels do not contain a large enough proportion of VC type carbides to impart good cutting properties to the steel.

With respect to the cost of making my steel, it is pointed out that tungsten is a very expensive alloying element and that my steels contain relatively low percentages of it or none at all. In addition, the total alloying content of my steels is relatively low. For example, the cost of the ingredients of my steel S is approximately one-third that of the ingredients for steel A, five-eighths that of steel E and five-sixths that of steel D.

I claim:

1. A low alloy, high speed steel consisting essentially of 4.79 to 5.97 atomic percent carbon, 3.70 to 4.80 atomic percent chromium, 3.98 to 4.86 atomic percent vanadium, 1.25 to 3.42 atomic percent molybdenum, and 0 to 1.05 atomic percent tungsten, the balance being substantially all iron, the steel complying with Rule 1 $C_t-(C_v+C_m)=-0.10$ to -0.40 atomic percent and also complying with Rule 2

$$\frac{C_v}{C_t - C_v} = 4 \text{ to } 6$$

in which C_t is the atomic percent of all the carbon in the steel, C_v is the atomic percent of carbon needed to combine with all the vanadium in the steel to form VC, and C_m is the atomic percent of carbon needed to combine with all the tungsten, chromium and molybdenum in the steel to form $(W, Cr, Mo)_6C$ type carbides.

2. A low alloy, high speed steel consisting essentially of 4.79 to 5.97 atomic percent carbon, 3.70 to 4.80 atomic percent chromium, 3.98 to 4.86 atomic percent vanadium, 1.25 to 2.01 atomic percent molybdenum, and 0.66 to 1.05 atomic percent tungsten, the balance being substantially all iron, the steel complying with Rule 1 $C_t-(C_v+C_m)=-0.10$ to -0.40 atomic percent and also complying with Rule 2

$$\frac{C_v}{C_t - C_v} = 4 \text{ to } 6$$

in which C_t is the atomic percent of all the carbon in the steel, C_v is the atomic percent of carbon needed to combine with all the vanadium in the steel to form VC, and C_m is the atomic percent of carbon needed to combine with all the tungsten, chromium and molybdenum in the steel to form $(W, Cr, Mo)_6C$ type carbides.

3. A low alloy, high speed steel consisting essentially of about 1.29 percent carbon, about 4.45 percent chromium, about 3.47 percent molybdenum, about 4.61 percent vanadium, and about 3.54 percent tungsten, the balance being substantially all iron.

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