cent., 26·4 per cent., and 28·42 per cent. Nickel they are non-magnetic. Further increases of Nickel, 35·09 per cent., 49·08 per cent., and 75·06 per cent., restored the magnetic properties very markedly, the maximum values being obtained with 47·08 per cent. Annealing at 675° resulted in general in an improvement of magnetic quality. Annealing at 1,000° for the bars with smaller Nickel content resulted in an increase of permeability for lower magnetising forces, and bars containing 25·2 and 26·4 per cent. Nickel became appreciably magnetic.

Hysteresis curves were taken on the alloys showing higher permeability, and it was found that the 50 per cent. Nickel alloy had the lowest loss. The electrical resistance was also determined, and it was found that there was a gradual increase of resistance with increase of Nickel up to 22·11 per cent., after which there was a sudden rise at compositions corresponding to those of the non-magnetic alloys. Beyond about 30 per cent. Nickel a decrease is noticed, giving a curve similar to that on the other side of the maximum range. It is suggested that the maximum point might correspond to the compound **Fe_2Ni.**

An alloy containing 35 to 36 per cent. Nickel is known to have a dilatation ten times less than that of Platinum. The expansion in the case of Nickel steels is said to be much more feeble in the magnetic than in the non-magnetic state. Again, it has been shown by Guillaume that a Nickel steel bar containing 15 per cent. Nickel, allowed to cool very slowly from 200° C., contracted until the temperature reached 130° C., when the bar began to expand, and continued to do so until 60° C. If such a bar be heated when below 130° C. very slightly it expands like an ordinary metal, and on again cooling contracts correspondingly until the temperature at which the heating began is reached, when the bar again begins to expand.

As regards non-corrosion, Nickel steel gives far better results than either wrought iron or ordinary mild steel. The following table shows the relative corrosion of wrought iron, soft steel, and Nickel steel (taking wrought iron as a standard), from experiments published in 1900 by Prof. Howe. The specimens treated were exposed for periods of about a year each :—

TABLE LXXXIII.

	Sea Water.	Fresh Water.	Weather.	Average.
Wrought iron, ...	100	100	100	100
Soft steel, ...	114	94	103	103
3 per cent. nickel steel, . .	83	80	67	77
26 " " . .	32	32	30	31

Steel containing **Nickel** and **Chromium** has been found to give satisfactory results when used for armour plate and also for armour piercing shells, and plates of the following approximate composition have been used :—

	Per cent.	Per cent.	Per cent.
Combined	**C,** 0·40	**Cr,** 1·0	**Ni,** 2·0

here the Nickel may be considered as a *toughening* agent, and the Chromium and Carbon as *hardening* agents.

Nickel-Chrome steel is also largely used on the Continent for manufacture of large guns and also to a more limited extent in this country.

Some interesting results upon alloys containing Nickel, Chromium, and Silicon made at the Imphy Works have been published by A. Abraham.[*] Steels of the following composition,

Carbon, ...	·55 to ·80
Silicon, ...	·20 to ·50
Manganese, ...	·30 to ·60
Chromium, ...	2·00 to 3·00
Nickel, ...	20·00 to 25·00

tested after forging without any special treatment, gave an elastic limit exceeding 31 tons, with an ultimate tensile resistance of 44½ tons, and an elongation of 45 per cent. on 2 inches. In this condition they were wanting in flexibility, and were better after being subjected to water hardening at a cherry-red heat without further tempering. After this they gave an elastic limit of from 19 to 22 tons, with an elongation of 60 per cent., the elongation taking place over the entire length of the test piece. Another class of steel made at Imphy with Nickel from 12 to 12·5 per cent. ; Chromium, ·75 to 1 per cent. ; Carbon, ·3 to ·45 per cent., was found to be much harder, breaking almost without stretching in its natural state. After annealing in a wood fire it gave a material suitable for forgings requiring high tenacity and elasticity, the elastic limit exceeding 51 tons, with an ultimate strength of 63½ tons.

Silicon.—See influence of Silicon on steels, p. 365*a*.

Tantalum.—Comparatively little is known of the properties of Tantalum steels, but from researches carried out by Guillet,[†] it would appear that the effect of Tantalum is too small to enable these steels to attain any special technical importance. Guillet prepared his steels from Tantalum-Iron made in the electric furnace. The steels examined had the following composition :—

TABLE LXXXIV.

C.	Ta.	Mn.	Si.	S.	P.
0·12	0·09	0·19	0·12	trace	trace
0·17	0·15	0·15	0·19	..	..
0·18	0·60	0·22	0·24	..	..
0·16	1·05	0·23	0·16	..	..

The steels in the normal condition indicated the usual Pearlite structure with Ferrite, the greater the percentage of Tantalum, the more regular was the distribution of the Pearlite.

The following tables show the influence of Tantalum on the physical properties, in normal and hardened condition :—

TABLE LXXXV.—NORMAL STEELS.

Ta.	Elastic Limit.	Maximum Stress.	Elongation.	Reduction of Area.	Brinell Hardness.
	Kgs per Sq. Mm.	Kgs. per Sq. Mm.	Per cent.		No.
0·09	29·8	41·5	53	67·4	107
0·15	30·4	42·6	31	68·8	107
0·60	31·1	45·3	28	67·4	112
1·05	31·5	47·0	28	62·3	116

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[*] *Annales des Mines*, vol. xiv., p. 228, 1898.

[†] *Comptes rendus*, vol. cxlv., p. 327.

It will be noticed from the above that the elastic limit and breaking strength are slightly increased, and the elongation and reduction of area are slightly decreased by the presence of Tantalum.

TABLE LXXXVI.—HARDENED STEELS.

Ta.	Elastic Limit.	Maximum Stress.	Elongation	Reduction of Area.	Brinell Hardness.
	Kgs. per Sq. Mm.	Kgs. per Sq. Mm.	Per cent.		No.
0·09	46·2	65·0	14·5	71·0	159
0·15	45·7	62·1	15·0	73·1	153
0·60	46·6	65·8	13·0	74·9	155
1·05	49·1	70·0	10·0	55·8	169

The above tests of hardened steels were obtained from specimens hardened at 875° in water at 20° C.

Titanium.—This can be obtained in grey cast iron when smelted from Titanic ores with considerable ease, but it is very difficult to introduce this element into steel. Much of the so-called Titanic steel is quite innocent of the presence of this element. It appears, however, possible to make it from Ferro-Titanium.

As an example of the difficulty of introducing Titanium into steel, the following experiments by Mr. W. H. S. Shakell may be cited. Some of the titaniferous iron sand of New Zealand of the following composition :—

Peroxide of Iron,	67·04
Protoxide of Iron,	30·17
Oxide of Manganese,	0·22
Alumina,	0·16
Silicon,	0·50
Lime,	Trace
Magnesia,	Trace
Titanium,	1·60
Alkalies,	Not determined
	99·69

was mixed with suitable fluxes and reduced by coke in clay crucibles, and a white pig-iron containing about 2 to 3 per cent. of Titanium was obtained. The metal from three different experiments was then broken and mixed together with a small quantity of oxidised metal and about 8 ozs. of Ferro-Manganese, and re-melted in a crucible furnace, when a steel of the following composition was obtained :—

Iron,	98·400
Combined Carbon,	0·700
Graphite,	Trace
Silicon,	0·112
Manganese,	0·623
Sulphur,	0·098
Phosphorus,	0·030
Titanium,	Nil
	99·963

This ingot forged well under the hammer, and made a fairly good chisel.

This seems very clearly to show that Titanium is much more easily oxidised than Silicon, and this should have an important bearing on the future development of the large Swedish and other iron ore deposits containing Titanium, as if it can be proved that the Titanium in the pig-iron is oxidised completely during the conversion into steel, pig-iron containing Titanium can be used, and it only remains for the blast furnace manager to overcome any difficulties there may be in the smelting of such ores.

Ferro-Titanium is made in the electric furnace, and is sold as "Titanium alloy"; it may contain 10 to 15 per cent. of Titanium, 5 to 7 per cent. of Carbon, and less than 0·5 per cent. of other impurities. Many contradictory statements have been made as to the effect of Titanium on the properties of steel, and this may be considered as not yet definitely thrashed out. Some investigators * claim that Titanium acts as a deoxidiser, and that the Titanic Oxide formed acts as a flux for Silicates, yielding a more fluid slag than Aluminium, and so frees the steel from slag inclusions, and that it also renders the metal free from blowholes, increasing the elastic limit and reduction of area. The Titanium itself passes off with the slag unless added in excessive amounts. It has been claimed that Titanium actually reduces the amount of Sulphur and Phosphorus in the metal, but later experiments have not confirmed this, although the obnoxious effect of these elements appeared to be diminished. It is further claimed that Titanium increases the strength of Nickel and Chrome-Nickel steels, acting as a powerful deoxidising agent, and that it also removes Nitrogen from steel, a point to which particular importance has been attached by some metallurgists. Aluminium should not be used in connection with Titanium alloy at any time. Comstock recommends that the Titanium should be added in the form of Titanium Carbide, a product of the electric furnace, in quantity equivalent to 0·1 per cent. Titanium in the molten steel, which gives up to 0·025 per cent. Titanium in the finished steel.

Tungsten.—This is an exceedingly infusible metal which alloys with iron in nearly all proportions to form Ferro-Tungsten. Analyses of rich Ferro-Tungsten now on the market gave the following figures :—

Tungsten,	76·900
Iron,	17·950
Silicon,	1·900
Carbon (combined),	3·300
Phosphorus,	0·013
	100·063

Tungsten,	73·05
Iron,	22·55
Silicon,	0·48
Carbon (combined),	1·90
Phosphorus,	0·02
Sulphur,	0·05
Manganese,	0·34
Chromium,	1·02
Copper,	0·01
Tin,	0·18
Nickel,	0·22

Ferro-Tungsten can be made in the blast furnace, but such alloys as the above are usually made in the electric furnace. Tungsten can be reduced from the ore (generally Wolframite) by strong ignition with Carbon in crucibles.

The reduction of Wolfram ore by coke in the presence of pig-iron in

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* C. V. Slocum, *Mechanical Engineer*, vol. xxiii., pp. 336-337, 1909; Comstock, *Industrial and Engineering Chemical Journal*, Feb. 1915, p. 87.

crucibles is comparatively easy if a low percentage Ferro-Tungsten is required, but the resulting Ferro-Tungsten has to be broken up and re-melted to insure a uniform product. Tungsten is chiefly used as an alloy with steel for the production of so-called "self-hardening" steels—*i.e.*, steels which after forging require no quenching or tempering. The following analyses (Table lxxxvii.) show that these steels may vary very considerably in chemical composition, and the temperature at which they can be forged will vary with the composition:—

TABLE LXXXVII.

Temperature Worked.	Mushet.	Crescent.	Imperial.
°F.			
1264 Light yellow.	Cracks badly.	Crumbles badly.	...
1155 Yellow.	Forges.	Bends fairly.	Forges, but cracks.
1111 Orange.	Bends well.	...	...
750 Full red.	Bends and hammers close without cracking.	Bends well.	...
700 Low red.	Cracks in bending.	Breaks when bent.	Bends double and hammers close without cracking.
525 Black.	...	Cracks after few blows.	Forges better than at temperatures given above.
	Per cent. Mushet— **C** (combined), 1·99 **Si**, . . 0·09 **Mn**, . . 0·19 **W**, . . 7·81	Per cent. Crescent— **C** (combined), 2·06 **Si**, . . 0·05 **Mn**, . . 2·66 **W**, . . 6·73	Per cent. Imperial— **C** (combined), 1·60 **Si**, . . 0·16 **Mn**, . . 2·11 **W**, . . 6·38

N.B.—Crescent appears to forge better at a low yellow heat.
Imperial " " dull red "

Mr. W. H. S. Shakell informs me he has obtained from a charge of the following composition, a steel which worked remarkably well under the hammer at a low red heat (about 700°), and made capital turning tools:—

Charge.

	lbs.	ozs.
Steel scrap, ...	26	0
Ferro-Tungsten, ...	9	0
Silico-Spiegel, ...	0	10
Ferro-Manganese, ...	0	2
Swedish pig-iron, ...	9	4
	45	0

Drillings taken from the resulting ingot gave the following chemical composition:—

Per cent.	Per cent.	Per cent.	Per cent.
Combined **C**, 1·01	**Si**, 0·186	**Mn**, 0·738	**W**, 6·975

A small addition of Tungsten has been found to improve the wearing properties of some classes of chisel steel; for instance, a steel of the following composition gave good results for the working of pyrites, whilst a steel of similar composition, without the quarter per cent. of Tungsten, failed in a competitive trial:—

Per cent.	Per cent.	Per cent.	Per cent.	Per cent.	Per cent.	Per cent.
Fe, 98·40	Combined **C**, 0·63	**Si**, 0·126	**W**, 0·241	**Mn**, 0·522	**S**, ·006	**P**, ·034

A steel containing

Per cent.	Per cent.	Per cent.
Combined **C**, ·57	**Si**, ·21	**W**, ·325

also stood this class of work well, where a somewhat higher Carbon steel (without Tungsten) failed to do the work satisfactorily.

Tungsten when added to low Carbon steel has very little effect on the magnetic properties, but greatly increases the retentiveness in high Carbon steels, and a steel having the following composition:—

Per cent.	Per cent.	Per cent.	Per cent.	Per cent.	Per cent.
Combined **C**, 0·62	**Si**, ·09	**Mn**, ·55	**W**, 5·7	**S**, ·04	**P**, ·045

is found to give very satisfactory results for the manufacture of permanent magnets, used in the construction of electrical meters.

These steels are preferably made from charges melted in crucibles, and cast into small ingots about 3 inches square, each weighing about 56 lbs. This steel requires careful heating and "soaking" before hammering, and should not be worked above a full red heat.

Tungsten, in the absence of Carbon, has comparatively little influence on the physical properties of steel, but when alloyed with Carbon steels confers upon them great hardness. The well-known Mushet or self-hardening steel contains about 1·5 to 2·3 per cent. Carbon and from about 5 to 8 per cent. Tungsten. These steels, on heating and allowing to cool in air, are extremely hard, and retain their cutting edges for a long time even when used for machining very hard material; if quenched at a red heat in water in the same way as ordinary steels, they crack.

The following are typical analyses given by Hadfield[*]:—

Carbon.	Silicon.	Sulphur.	Manganese.	Tungsten.
2·30	1·05	..	2·57	6·12
2·00	1·60	0·02	1·72	8·22
2·05	0·79	0·04	2·30	8·04
1·67	0·33	..	2·53	5·74
2·35	0·15	..	3·38	11·02

The first two are the well-known Mushet steel.

The high percentage alloys, however, are somewhat brittle and can only be used in cases where there is no shock or jar, such as, for instance, cutting purposes in the lathe.

In steels containing more than 11 per cent. of Tungsten, a Carbide is formed having the formula **WC**, which entirely displaces $\mathbf{Fe_3C}$.[†]

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[*] *Iron and Steel Inst. Journ.*, 1903, vol. ii.

[†] Arnold and Read, *Proc. Institution Mechanical Engineers*, 1914, p. 228.

The constitution of Tungsten steels is stated by Guillet[*] to be Pearlitic up to 9 per cent. of Tungsten when 0·2 per cent. Carbon is present, and up to 4·5 per cent. Tungsten when 0·8 per cent. Carbon is present, when these amounts of Tungsten are exceeded, however, free Carbide is found in the steel.

Edwards[†] considers that the formation of Tungsten Carbide is accelerated by the presence of Chromium.

A new class of cutting tool for machine work at very high speeds has been introduced, the alloys used being a Chromium-Tungsten or Chromium-Molybdenum steel, specially tempered. The material was exhibited at the Paris Exhibition of 1900 by the Bethlehem Steel Company, and was shown at work on mild steel castings at a speed of 150 feet per minute, without lubricants. The cutting edge of the tool was red hot, whilst the turnings showed, from the colour when cold, that they had been exposed to very considerable heat. The percentage composition of the tools varies with the work to be done, from about ·75 per cent. of Chromium, with some 4 per cent. of Tungsten and traces of Molybdenum, to 3 per cent. Chromium, 8 per cent. Tungsten, and varying percentages of Molybdenum. For working hard steel or chilled iron the alloy contains about 3 per cent. of Chromium, 5 per cent. of Tungsten, and 4 per cent. of Molybdenum. The great advantage such steel possesses over the ordinary "self-hardening" is imparted to it by the special heat treatment to which it is subjected. The steel is first heated to about 1,000° C., then rapidly cooled down in a bath of molten lead, kept at that temperature for about ten minutes, and then allowed to slowly cool in lime, or some other inert non-conducting body. For some purposes when quite cold it is re-heated to visible red, and allowed to cool in the open air. The surface of the tool is protected during this treatment by being covered with a suitable flux so as to prevent oxidation.

The above method of treating self-hardening steels was only discovered by Messrs. Taylor and White after a most careful series of experiments, as previous to their investigations the greatest care was always taken not to heat these self-hardening steels above 800° C. during forging, any temperature above this spoiling the steel. We owe to them the important discovery that by heating to a temperature *far* above the temperature at which the metal would forge, and by *regular cooling*, this great increase of hardness was imparted.

Osmond[‡] in 1892, in experimenting with a Tungsten steel, found that when heated to 830° and quenched at 630°, it remained unhardened, but when heated to 1,310° and quenched at a lower temperature—viz., 555°—it was very hard, and he at once noticed the important point that a soft medium or very hard metal could be obtained according as the initial temperature of heating was varied. These results were, however, never published, so that Messrs. Taylor and White's discovery was quite independent of these experiments.

According to Mr. D. Flather,[§] it appears as if some of the details of the above method are unnecessary. Several brands of steel are at present made at Sheffield, and the method of hardening is said to be much simpler than that above described. The steel is heated to near a welding heat (1,200° C.), and is then either cooled in the air or under an air blast, when, after being ground, it is ready for use.

One such Sheffield brand of steel is that known as the "Speedicut," manufactured by Messrs. Thos. Firth & Sons. The method of manufacture and treatment is kept a secret, so the author is unable to give any information on these points, but it is extremely hard naturally, and will do excellent work at a just visible red heat. It can be forged by any intelligent tool smith, and does not require to be hardened in water or other medium, and allows a lathe to be run at two or three times the usual speed. Probably any method of heating the steel to a very high temperature, combined with *slow and regular cooling*, would produce the desired results, these being the two essential conditions in the treatment of these steels. Such steels as these mark a new epoch in the history of tool steels, and will probably largely revolutionise many of our machine shops.

Some years ago the author conducted a long series of experiments on the influence of Tungsten on mild steel containing about ·1 per cent. of Carbon, made in a Hatton converter. The alloys made varied from traces to 1·58 per cent. of Tungsten, and the results of mechanical tests on the samples as rolled and after quenching, together with welding, plating, and cold-bending tests, are given in Table lxxxviii. So far as these results go, neither the *tensile strength, elongation*, nor *reduction of area* appears to be appreciably affected by ·8 per cent. of Tungsten, and even 1·5 per cent. only increases the tensile strength by a few tons. The *hardening effect*, so far as this is indicated by cold-bend tests, is not apparent with ·8 per cent., all the 1-inch round bars bending over close up to this point. With 1·5 per cent. of Tungsten the influence of Tungsten is noticeable in the cold bending, one bar breaking after bending over only 15° and a duplicate at 110°, showing that such metal was distinctly less ductile than that containing less Tungsten, and it is probable that, had there been an alloy between ·8 and 1·5 per cent., this hardening effect might have been noticeable with less Tungsten present. Tungsten apparently has no effect on the welding or forging properties, as shown by the plating out and welding tests, those cases where the material welded badly being evidently due to bad workmanship or some cause other than the presence of Tungsten, as proved by the alloys with larger percentages giving good results. The cold bendings were made with a sledge hammer on the 1-inch bars as rolled.

Since these results were obtained Hadfield has read a paper before the 1903 autumn meeting of the Iron and Steel Institute, giving the results of a very complete series of experiments on steel containing from ·1 to 16 per cent. of Tungsten. Up to 1·49 per cent. Tungsten, the Carbon does not exceed ·22 per cent., and the steels may therefore be regarded as strictly comparable with the author's, and the results, with the exception of welding, completely confirm those given in Table lxxxviii. Neither the tensile stress, elastic limit, elongation, nor reduction of area is appreciably affected until the steel contains 3·4 per cent. of Tungsten, and in the annealed samples even 7·47 to 8·3 per cent. does not greatly increase the tenacity. In the bending tests, the samples as rolled showed no apparent hardening until 3·4 per cent. Tungsten was reached, and, when water quenched from a temperature between 750° and 950° C., not until the steel contained 1·2 per cent. In the author's experiments all the bars *as rolled* bent close, and, in the *quenched* samples, the first hardening effect, which could be credited to

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[*] *Iron and Steel Inst. Journ.*, 1906, No. 2, p. 10.

[†] *Ibid.*, 1908, No. 2, p. 132.

[‡] *Ibid.*, 1903, vol. ii.

[§] *Iron and Coal Trades Review*, December 27, 1901.

TABLE LXXXVIII.—AUTHOR'S RESULTS.

ANALYSES AND MECHANICAL TESTS OF TUNGSTEN STEEL.

No.	ANALYSES.						MECHANICAL TESTS.														REMARKS.
							Cold Tests		Hot Tests.		Machine Tests on Bars as Rolled in Tons per Square Inch. Elongation, 8 inches.					Machine Tests on Quenched Bars in Tons per Square Inch. Elongation, 8 inches.					
	Silicon.	Phos-phorus.	Manganese	Sulphur.	Carbon.	Tungsten.	Bars as Rolled.	Rolled Bars Quenched.	Plating.	Welding.	Maximum Stress.	Elastic Limit.	Elongation.	Reduction of Area.	Fracture.	Maximum Stress.	Elastic Limit.	Elongation.	Reduction of Area.	Fracture.	
A	trace	·071	·394	·064	·100	nil	Bent over close.	Bent over close.	Very good.	Very good.	27·3	20·9	27·8	59·0	Silky.	37·5	25·9	15·6	50·9	Silky.	
B	,,	·075	·341	·040	·095	trace	,,	,,	,,	,,	27·7	21·7	23·1	43·2	..	39·0	25·9	17·5	50·0	,,	
C	,,	·076	·537	·054	·120	,,	,,	,,	,,	,,	29·8	21·2	25·6	56·2	..	42·9	26·3	15·0	49·1	,,	
D	,,	·040	·207	·029	·070	,,	,,	,,	Fair.	Good.	24·3	17·4	28·1	76·0	..	5·9	16·1	23·7	65·5	,,	
E	,,	·070	·570	·054	·130	,,	,,	,,	Very good.	Very good.	30·3	21·0	15·8	42·3	Crystalline.	40·9	25·1	17·5	52·3	,,	
F	,,	·074	·561	·052	·135	0·010	,,	Broke at angle 15°.	,,	,,	30·5	21·2	23·7	44·8	..	39·7	28·9	10·6	45·0	,,	
G	,,	·070	·382	·071	·110	0·050	,,	Parallel, then broke	Poor.	Poor.	28·2	21·1	25·0	58·3	..	39·2	26·3	13·7	32·7	Crystalline.	Broke near mark.
H	,,	·049	·241	·046	·070	0·210	,,	Bent over close.	Fair.	Very good.	24·8	17·2	26·9	63·7	..	35·1	21·4	15·2	55·3	Silky.	
I	,,	·070	·491	·024	·110	0·285	,,		Very good.	,,	29·6	22·3	21·2	47·7	..	39·4	25·6	11·2	14·2	Crystalline.	
J	,,	·068	·474	·017	·115	0·310	,,	,,	,,	Fair.	29·0	21·9	25·0	59·5	..	39·4	26·3	13·1	30·6	Silky.	
K	,,	·063	·231	·043	·115	0·361	,,	Broke at angle 140°. Check ,, 15°.	,,	Bad.	26·8	20·3	25·0	55·8	..	41·1	28·8	11·8	32·0	Crystalline.	
L	,,	·048	·184	·031	·070	0·415	,,	Bent over close.	Poor.	,,	22·6	17·8	27·5	78·8	..	29·8	18·1	25·0	65·2	Silky.	
M	,,	·053	·416	·043	·130	0·517	,,	Bent over close, then broke. Check ,,	Very good.	Very good.	27·9	20·3	23·4	62·1	..	44·2	28·5	15·6	46·8	,,	
N	,,	·050	·369	·035	·125	0·524	,,	Bent over close.	,,	,,	28·7	20·0	20·6	41·9	..	43·1	27·1	15·6	46·4	,,	,,
O	,,	·073	·243	·054	·080	0·731	,,	,,	,,	Bad.	27·6	21·3	21·9	38·6	..	40·3	24·7	14·3	43·8	,,	
P	,,	·C76	·372	·053	·145	0·800	,,	,,	,,	Very good.	28·9	21·5	25·0	58·5	..	43·6	26·8	11·8	52·7	,,	
Q	,,	·035	·468	·019	·220	1·580	,,	Broke at angle 15°. Check ,, 110°.	,,	,,	31·1	19·2	24·7	64·2	..	40·8	22·9	9·3	3·6	,,	,,

TABLE LXXXIX.—HADFIELD'S RESULTS.

GENERAL TABLE, SHOWING ANALYSIS, ELASTIC LIMIT, BREAKING LOAD, ELONGATION, REDUCTION OF AREA, BENDING AND WELDING QUALITIES OF UNANNEALED AND ANNEALED FORGED TUNGSTEN-IRON ALLOYS.

Marks.	ANALYSES PER CENT.							Limit of Elasticity per Square Inch.	Maximum Stress per Square Inch on Original Area.	Total Elongation per cent. on 2 Inches.	Reduction of Area per cent.	Appearance of Fractured Test Bar.	Bending Tests of Unannealed and Annealed Forged Bars, Inch wide and Inch thick.	Welding Test.
	Carbon.	Silicon.	Sulphur.	Phos-phorus.	Man-ganese.	Tungsten.		Tons.	Tons.					
A	·13	·03	·12	·06	·22	0·10	Unannealed.	20·0	25·50	35·30	60·74	Dark granular; fibrous and silky.	Double, unbroken.	...
							Annealed.	14·5	22·50	43·10	65·46		,, ,,	...
B	·15	·04	...	...	·22	0·20	Unannealed.	22·5	27·50	40·85	60·74	Granular; fibrous; silky at edges.	,, ,,	Would not weld.
							Annealed.	16·5	22·50	46·30	66·48		,, ,,	
C	·15	·07	·10	·08	·29	0·40	Unannealed.	24·0	31·00	33·00	59·80	Granular; fibrous; silky.	,, ,,	...
							Annealed.	18·0	25·50	39·60	60·10	,, ,, ,,	,, ,,	...
D	·13	·04	...	...	·18	0·35	Unannealed.	20·0	27·50	37·35	58·34	Granular; fibrous; silky at edges.	,, ,,	Would not weld.
							Annealed.	16·5	23·00	44·95	68·90		,, ,,	
E	·21	·05	...	...	·18	0·81	Unannealed.	29·0	32·25	35·28	63·36	Dark granular; fibrous; silky.	,, ,,	,,
							Annealed.	18·0	26·25	37·60	53·26		,, ,,	
F	·22	·05	...	...	·18	1·20	Unannealed.	25·0	32·50	25·75	49·34	Dark granular; fibrous and silky.	,, ,,	,,
							Annealed.	17·5	27·00	37·68	54·38		,, ,,	
G	·21	·07	·12	·07	·25	1·49	Unannealed.	20·0	34·50	26·35	46·72	Granular; fibrous; silky at edges.	,, ,,	,,
							Annealed.	19·5	28·50	36·90	54·88		,, ,,	
H	·28	·06	·10	·06	·28	3·40	Unannealed.	31·0	41·00	29·50	51·80	Granular; fibrous; silky at edges.	110°, broken.	...
							Annealed.	23·0	34·00	33·90	53·02		Double, unbroken.	...
I	·38	·11	...	...	·20	7·47	Unannealed.	37·5	63·00	14·15	18·42	Very fine dark crystalline, with dark spot at edge from which fracture radiates.	84°, broken.	...
							Annealed.	24·0	40·00	25·65	38·46		Double, unbroken.	...
J	·46	·08	...	·06	·28	8·33	Unannealed.	45·0	64·00	2·50	2·48	Fine crystalline, with small defect at edge.	45°, broken.	...
							Annealed.	25·5	42·50	22·80	32·62		Double, unbroken.	...
K	·63	·10	...	...	·25	10·56	Unannealed.	55·0	80·00	5·19	4·80	Very fine dark crystalline.	10°, broken.	...
							Annealed.	28·5	48·00	10·00	10·24		Double, unbroken.	...
L	·76	·19	...	...	·28	15·65	Unannealed.	* ...	...	...	...	... ...	5°, broken.	...
							Annealed.	27·5	57·00	3·45	2·56	... ...	168°, ,,	...
M	·78	·15	·15	·04	·27	16·18	Unannealed.	Bar had been measured up to 50 tons, but no set observed.	Broke short at 55 tons.	0·46	0·28	Fine crystalline.	3°, ,,	...
							Annealed.	27·5	43·00	1·45	0·74	,,	95°, ,,	...

* Too hard to machine in unannealed condition.

the presence of Tungsten, was apparent with the 1·58 per cent. Tungsten steel, there being no alloy between this and the ·8 per cent. The Hadfield compression tests generally confirm the tensile results.

With regard to welding, Hadfield finds that so small a percentage as ·2 of Tungsten prevents welding, whereas the author's samples, with 1·5 per cent., welded well. Appended is a table giving full particulars of Hadfield's results (see Table lxxxix., p. 419). At first sight it seems difficult to explain this different behaviour of the two sets of alloys, but, on carefully examining the analyses of the author's samples, it will be found that the only three containing any appreciable amount of Tungsten which welded badly were K, L, and O, all of which were very low in Manganese, containing less than ·25 per cent. The other samples, fairly high in Manganese, all welded well. On reference to the Hadfield samples, although the percentage of Sulphur is not given in all cases, where it is given it is always high, the lowest percentage being ·1 and the highest ·15; the Manganese in all cases is also very low, the highest percentage being only ·28 and lowest ·18. Bearing these facts in mind, it does not seem improbable that any tendency to red shortness, induced by the presence of Tungsten, may have been greatly increased by the absence of Manganese and the presence of a comparatively large percentage of Sulphur, and, given a larger percentage of Manganese and lower Sulphur, some of the Hadfield samples which refused to weld might have given much better results. It thus seems probable that Tungsten *per se* up to 1·5 per cent. does not prevent welding of mild steel, except in cases where the general composition of the steel would lead us to expect doubtful results, when it increases the evil. The action, however, of Tungsten on the welding properties requires further experimental evidence before the matter can be considered finally settled.

Tungsten steels are largely used for permanent magnets, and G. Hannack * has pointed out that Carbon and Tungsten are by far the most important constituents of magnet steels. Manganese is found to reduce the capacity, and should not be higher than 0·2 per cent.; Silicon in small quantities is not detrimental, and Sulphur and Phosphorus have no influence of the capacity or permanence of magnet steels. Copper and Nickel are found to be detrimental. A steel of the following composition is stated to be excellent for magnets:—**C** 0·6, **W** 5·37, **Mn** 0·18, **P** 0·02, **S** 0·038, **Si** 0·25, **Cu** 0·004.

For the best results, this steel should be hardened at about 850° C.

Molybdenum may be used instead of Tungsten, but Chromium is inferior in its effect.

Uranium.—Very little is known of the properties of Uranium steels, but Uranium † is said to increase the hardness, toughness, and elasticity of steel, although not to the same extent as Vanadium, Chromium, Nickel, or Tungsten. Uranium steels are claimed to be specially suitable for ordnance and armour plate.

Vanadium.—The general effect of Vanadium on steel seems to be to increase the tensile strength and elastic limit and somewhat reduce the elongation.

The experiments made during the last few years—*i.e.*, since Vanadium

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* *Stahl und Eisen*, 1908, vol. xxviii., pp. 1237-1240; see also *Mechanical Engineer*, 1910, vol. xxv., pp. 331-332.

† *Oesterr. Zeit. für Berg. und Huttenwesen*, vol. lvii., p. 313.

TABLE XC.—INFLUENCE OF VANADIUM ON ORDINARY MILD STEEL AND ON MILD NICKEL STEEL.

No.	Carbon.	Vanadium.	Nickel.	Silicon.	Manganese.	Sulphur.	Phosphorus.	Area.	Elastic Limit per Square Inch.		Maximum Stress per Square Inch.		Elongation per cent. in 2 Inches.	Reduction of Area.
								Sq. Ins.	Lbs.	Tons.	Lbs.	Tons.		Per cent.
Bars as rolled.														
682*	0·22	None.	None.	0·083	0·24	0·02	0·015	0·25	57,615	25·72	68,650	30·64	33·5	60·1
683	0·20	0·27	,,	0·092	0·48	...	...	,,	83,776	37·40	105,500	47·08	22·0	51·4
684	0·25	None.	3·35	0·084	0·46	...	...	,,	73,024	32·60	94,528	42·20	26·5	52·8
685	0·24	0·28	3·38	0·091	0·48	...	...	,,	112,650	50·28	152,678	68·16	17·0	36·3
Bars reheated to 800°, allowed to cool in air.														
682*	0·22	None.	None.	0·083	0·24	0·02	0·015	0·25	51,856	23·16	63,428	28·32	37·5	64·5
683	0·20	0·27	,,	0·092	0·48	...	...	,,	63,168	28·20	81,190	36·24	29·5	59·4
684	0·25	None.	3·35	0·084	0·46	...	...	,,	70,890	31·64	92,054	41·08	28·5	56·9
685	0 24	0·28	3·38	0·091	0·48	...	...	,,	103,760	46·32	121,856	54·40	22·0	51·2
682†	0·22	None.	None.	0·083	0·24	0·02	0·015	0·355	43,130	19·26	63,930	28·53	2 ins. 42·0 4 ,, 31·0	51·5
683	0·20	0·27	,,	0·092	0·48	...	...	0·363	75,600	33·74	99,140	44·27	2 ,, 19·0 4 ,, 17·0	41·6
684	0·25	None.	3·35	0·084	0·46	...	...	,,	59,850	26·72	90,050	40·22	2 ,, 18·0 4 ,, 21·2	40·5
685	0·24	0·28	3·38	0·091	0·48	...	...	,,	91,840	41·01	158,873	70·93	2 ,, 10·0 4 ,, 9·7	11·9
695	0·18	0·61	None.	0·148	0·43	...	...	0·375	93,856	41·87	122,124	54·52	2 ,, 20·0 4 ,, 15·0	34·4

* Nos. 682 to 685 ¾-inch round bars. † Nos. 682 to 685 and 695 rolled into 3-inch by ⅜-inch plate. Test bars 1 inch wide.

Mark.	Size.			Bending Tests.		Remarks.
				Bent Cold over a Radius of	Bending Angle.	
682	12 inches ×	1 inch ×	⅜ inch.	⅜ inch.	180°, unbroken.	Closed without fracture.
683	,,	,,	,,	,,	,, ,,	Broke on closing. Steel much stiffer than 682.
684	,,	,,	,,	,,	,, ,,	Cracked on closing.
685	,,	,,	,,	,,	120°, broke.	Steel very stiff.
695	,,	,,	,,	,,	180°, unbroken; very stiff.	Broke on closing.

became obtainable at a more reasonable price—have demonstrated that it is probably one of the most powerful metals for alloying with steel yet discovered. One or two-tenths per cent. of Vanadium raises the elastic limit and tensile strength of mild or low Carbon steel by about 50 per cent., and in some cases even more.

Vanadium apparently acts to some extent in the same way as Aluminium as a deoxidiser, and it is also claimed that it removes Nitrogen in form of Nitrides, thus reducing the occluded gases in the steel. It appears to act directly in several different ways, in low and medium Carbon steels it toughens the metal mainly by its solid solution in the Carbonless portion or Ferrite; it also forms complex Carbides, which, especially with Chromium or Nickel, greatly strengthen the steel, and it seems to have a physical influence also, promoting the even distribution of the Carbon and considerably retarding constitutional segregation; from experimental evidence there is the strongest reason to believe that a very small percentage of Vanadium will largely enable the steel to resist that deterioration which, under continued vibration, leads to brittleness, and is one of the most serious dangers which engineers have to face in these days of high-speed engines with large moving parts.

Samples of steel alloyed with very small quantities of Vanadium have been produced and have given extraordinary results when tested mechanically. The results obtained with some experimental bars and plates from crucible steel with and without Nickel, for which I am indebted to the late Mr. A. F. Wiener, are given in Table xc., p. 421. The experiments were conducted by Prof. Arnold.

The round bar, 682 of ordinary steel, has an exceptionally high elastic limit, but in the plate samples is nearer normal, and no explanation of this can be given. It will be noticed that ·27 of Vanadium has raised the elastic limit 12 tons, and the maximum stress 16 tons per square inch, with only a fall of 11 per cent. in the elongation and 9 per cent. in the reduction of area, thus having a greater influence than 3·35 per cent. of Nickel. In the Vanadium-Nickel steel, 685, ·28 per cent. of Vanadium has raised the elastic limit 18 tons, and the maximum stress 26 tons per square inch, giving a steel with an elastic limit of 50 tons, and a maximum stress of over 68 tons per square inch, with an elongation of nearly 17 per cent., and a reduction of area of over 36 per cent.

The above results are confirmed by some given in the *Engineering and Mining Journal* of New York, of 18th August, 1900, where a wrought-iron bar containing 0·5 Vanadium gave 39 tons maximum stress with 12 per cent. elongation, compared with 24·5 tons and 19 per cent. elongation for the unalloyed iron. On annealing, the Vanadium bar gave 33·7 tons maximum stress with 32 per cent. elongation. A mild steel of 30 tons maximum stress and 17 per cent. elongation when alloyed with 1 per cent. Vanadium, gave a maximum stress of 61 tons and 14 per cent. elongation as rolled, and after annealing, 45 tons and 20 per cent. elongation.

When using Vanadium to alloy with steel it must be borne in mind that the element acts in the same direction as, but to a much more marked extent than, Carbon in steel, and that the percentage of Carbon must therefore be controlled with special care.

The following are some results with high Carbon steels kindly supplied me by Mr. Wiener, a bar of pure iron with ·85 per cent. of Vanadium being included in the test for comparison:—

TABLE XCI.—INFLUENCE OF VANADIUM ON HIGH CARBON STEELS.

Ingot Number.	Analyses.			Mechanical Results.			
	Combined Carbon.	Vanadium.	Aluminium.	Elastic Limit per Sq. Inch.	Maximum Stress per Sq. Inch.	Elongation per cent. in 2 Inches.	Reduction of Area.
	Per cent	Per cent.	Per cent.	Tons.	Tons.		Per cent
617 Steel,	1·06	0·14	0·07	43·0	67·9	6·5	6·9
618 ,,	1·02	0·29	0·09	43·2	76·2	8·5	10·0
619 ,,	1·00	0·58	0·36	64·8	85·5	7·0	7·6
620 Iron,	0·05	0·85	0·05	20·4	26·1	37·0	72·0
621 Steel,	0·80	1·11	0·45	54·0	77·1	10·0	17·6
622 ,,	1·04	0·77	0·21	58·8	84·0	7·5	9·3

Test bars. $\frac{3}{4}$-inch rounds.

The results of the mechanical tests prove beyond doubt the remarkably powerful influence of Vanadium on iron and steel. A pure iron ingot without Vanadium yields a bar having an elastic limit of 12 tons, and an ultimate stress of 21 tons per square inch, and also a reduction of area of about 75 per cent. Therefore, ·85 per cent. of Vanadium has raised the elastic limit 8 tons, and the ultimate stress 5 tons per square inch without appreciably reducing the ductility; its influence, however, on iron is not nearly so marked or extraordinary as its action upon steel.

A nearly pure iron and Carbon steel containing about 1·1 per cent. of Carbon has an elastic limit of about 30 tons, an ultimate stress of about 60 tons per square inch, together with an elongation on 2 inches and a reduction of area of about 8 per cent. each. On reference to the table, it will be seen that without appreciably altering the ductility, ·14 per cent. of Vanadium has raised the elastic limit 13 tons and the maximum stress about 7 tons per square inch.

Without lowering the ductility (if anything, raising it) ·3 per cent. of Vanadium raises the maximum stress to 76 tons, and ·6 per cent. raises it to 85 tons per square inch. There seems to be no advantage in adding beyond ·6 per cent., as the steel containing ·77 per cent. gave practically the same results as that containing ·58 per cent. of Vanadium.

The elastic limit of nearly 65 tons per square inch possessed by the steel last named is more than remarkable.

Vanadium has such a very high melting point that it is very difficult, if not impracticable, to alloy it with steel in the ordinary plant available at steel works. Ferro-Vanadium, however, which should contain not less than 25 or over 35 per cent. Vanadium, will alloy easily with steel either in the crucible or the open hearth furnace. Losses by oxidisation are possible, but can be largely avoided, and with care and the exercise of proper technical skill by the steel-makers this loss should never exceed ·10 per cent., and normally not more than ·07 per cent.; thus in open hearth practice to obtain ·3 per cent. of Vanadium in the steel it should only be necessary to add a quantity of the alloy equivalent to ·37 per cent. Vanadium.

The Ferro-Vanadium used should be as pure as possible. The alloy commercially obtainable sometimes contains appreciable quantities of Carbon or Aluminium, either of which elements, if added haphazard to steel, may render the effect of the Vanadium on steel partly illusory or disappointing. An alloy which has a low melting point, and which gives very good results in actual practice, contains about 30 to 40 per cent. Vanadium, 6 to 7 per cent. Silicon, and about 3 per cent. of Aluminium.

During the last few years several systematic researches on Vanadium steels have been carried out and the results published,* and I am indebted to Mr. Kent Smith for the following information as to the influence of Vanadium, based on his own experimental work. It will appear from his results that, quite apart from the question of cost, the useful application of Vanadium is confined to alloying very small percentages, and in the direction of the quaternary rather than in that of the ternary steels.

The following table illustrates the effect of Vanadium, both alone and when alloyed with Chromium, in raising the ultimate stress and the yield point without very appreciably reducing either the elongation or reduction of area:—

TABLE XCII.

Reference Letter.		Yield Point. Tons per Sq. In.	Ultimate Stress. Tons per Sq. In.	Elastic Ratio.	Elongation. Per cent. on 2".	Reduction of Area. Per cent.
	CRUCIBLE STEELS (Carbon, ·22% to ·25%)—					
A	Plain Carbon, Manganese, ...	16·0	27·0	·592	35·0	60·0
B	,, +0·5 % Chromium, ...	22·9	34·0	·673	33·0	60·6
C	,, +1·0 % ,, ...	25·0	38·2	·654	30·0	57·3
D	,, +0·1 % Vanadium, ...	28·5	34·8	·819	31·0	60·0
E	,, +0·15 % ,, ...	30·4	36·5	·833	26·0	59·0
F	,, +0·25 % ,, ...	34·1	39·3	·867	24·0	59·0
G	,, +1·0 % Chromium + 0·15 % Vanadium,	36·2	48·6	·745	24·0	56·6
H	,, +1·0 % ,, +0·25 % ,,	49·4	60·4	·818	18·5	46·3
I	NICKEL STEEL, ...	26·0	42·0	·619	24·0	50·0
K	,, +0·2% Vanadium, ...	52·1	57·9	·899	20·5	52·4
	OPEN HEARTH STEELS (Carbon, ·25 % to ·27 %)—					
L	Plain Carbon, Manganese, ...	17·7	32·2	·549	34·0	52·6
M	,, +1·0 % Chromium + 0·15 % Vanadium,	34·4	52·6	·654	25·0	55·5

The very marked influence of oil tempering on the static qualities of the Chrome Vanadium and Nickel Vanadium steels is shown in the following table, due in all probability to the retarding action which Vanadium apparently has on the segregation of the Carbides:—

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* Sankey and Kent Smith, *Inst. Mech. Eng.*, December, 1904; Guillet, *Iron and Steel Inst. Journ.*, vol. ii., 1905; Kent Smith, *ibid.*; Kent Smith, *Soc. Chem. Industry*, March, 1906; Kent Smith, *Staffordshire Iron and Steel Inst.*, February, 1906.

TABLE XCIII.

Reference No.		Yield Point. Tons per Sq. Inch.	Ultimate Stress. Tons per Sq. Inch.	Elastic Ratio.	Elongation on 2 Inches. Per cent.	Reduction of Area. Per cent.
	OPEN HEARTH CHROME VANADIUM STEELS—					
N	Tempered rolled bar of steel, **M**, Table xcii., .	43·4	53·6	·809	22·0	56·6
	Similar Steels—					
O	Motor crank-shaft forging, .	48·5	57·1	·849	22·5	49·0
P	Hollow gun axle, . . .	45·6	53·2	·857	20·0	54·9
Q	Automobile (solid) driving axle, ...	43·5	53·7	·810	21·0	60·7
	NICKEL VANADIUM STEEL—					
R	Tempered rolled bar of steel, **K**, Table xcii., .	80·3	82·7	·971	14·5	50·5
	OPEN HEARTH STEEL—					
S	Mild Chrome Vanadium steel, as rolled, ...	21·8	27·6	·789	38·0	63·0
S_1	The same, quenched from 850° C., ...	34·1	45·7	·746	22·0	61·6

The steel marked **S** is suitable for case hardening.

It is not only under static stress that Vanadium quaternary steels give such remarkable results, but under dynamic and vibratory stress the results are exceptionally good. By the judicious use of Vanadium, a material combining high tensile strength with resistance to sudden shock and vibratory stresses, so urgently required by engineers to meet the requirements of modern engineering practice, can be produced.

In the following tables (xciv., xcv., xcvi.) some results are given, an exceptionally high-class steel, far superior to most Carbon steels, being tested for comparison; this steel, marked **T**, gave the following results in the testing machine:—

Reference No.	Elastic Limit. Tons per Sq. Inch.	Ultimate Stress. Tons per Sq. Inch.	Elongation on 2 Ins. Per cent.	Reduction of Area. Per cent.
T	18·5	30·2	40·5	60·7

TABLE XCIV.—ALTERNATING STRESS (ARNOLD'S METHOD).

Reference No.		Table.	Number of Alternations before Fracture.
T	Carbon steel, ...	...	1,000
O	Vanadium Chrome steel, . . .	xciii.,	1,500
P	,, ,, . . .	,,	1,600
Q	,, ,, . . .	,,	1,700

The following results further illustrate the influence of Vanadium and Chromium on the static and dynamic qualities of steel:—

TABLE XCV.

Reference No.	Elastic Limit. Tons per Sq. Inch.	Ultimate Stress. Tons per Sq. Inch.	Elongation on 2 Inches. Per cent.	Reduction of Area. Per cent.	Resistance to Alternating Stress (Arnold) before Fracture.	Resistance to Rotary Vibration (Stead). Reversals before Fracture.
T Carbon steel, . .	18·5	30·2	40·5	60·7	1,050	6,600
U Vanadium Chr. steel,	21·0	39·0	34·5	53·1	2,200	...
V ,, ,,	29·4	42·9	33·0	60·7	2,100	65,700

In **U** and **V** we have two steels combining high tensile strength with ductility, and at the same time showing remarkable resistance to vibration and sudden shock

TABLE XCVI.—Impact Tests (Izod's Methods).

Reference No.	Table Reference for Tensile Results.	Resistance to Sudden Shock. Foot-lbs.
T Carbon steel, ...	...	13
O Vanadium Chrome steel, . .	xciii.,	11
P ,, ,, . .	,,	10
Q ,, ,, . .	,,	12
U ,, ,, . .	xcv.,	16
V ,, ,, . .	,,	15

The above steels are all comparatively low in Carbon, but that very high tensile strength, combined with ductility, can be obtained by alloying Vanadium with higher Carbon steels is shown by the results given below, obtained with a ·45 per cent. Carbon steel.

TABLE XCVII.

	Elastic Limit. Tons per Square Inch.	Ultimate Stress. Tons per Square Inch.	Elastic Ratio.	Elongation on 2 Inches. Per cent.	Reduction of Area. Per cent.
As forged, .	44·95	77·92	·577	19·0	50·4
Tempered, .	91·69	101·72	·901	7·5	17·7

In the case of ordinary Carbon steels, when the tensile strength is considerably increased by additions of Carbon, the ductility and resistance to shock are rapidly reduced, but, by the addition of Vanadium instead, the static strength is greatly increased, while the ductility and resistance to sudden shock are not appreciably decreased.

Judging from the results obtained in practice, Vanadium used in combination with Chromium seems to give the best results. A steel containing from ·24 to ·28 per cent. of Carbon, 1·0 per cent. Chromium, and ·16 per cent. Vanadium is recommended by Kent Smith for rapidly moving parts subjected to alternating and other complex stress, and this class of steel is more largely used than the higher Carbon steel. It can be used both in the annealed and oil-tempered condition, and in the former state has a tensile strength of about 36 tons with an elastic limit of 27 tons, and an elongation 30 per cent. on 2 inches; oil-tempered it gives 59 tons tensile, 50 tons elastic limit, and 18 per cent. elongation with 57 per cent. reduction of area. For springs a somewhat higher Carbon, ·41 to ·47 per cent., with ·80 to ·90 per cent. of Manganese, is recommended, and it is claimed that springs made from this steel withstand repeated alternations of stress in the neighbourhood of the elastic limit to a far greater extent than Carbon steels without taking permanent set. This steel has also given very satisfactory results for gears for motor cars, and a somewhat higher Carbon and lower Manganese steel has been used in the United States for tyres.

So far as my own experience goes, I have seen some excellent results with Chrome Vanadium steels in cases where a high tensile strength combined with resistance to vibration and shock were required, and, although at present the use of this steel is limited, it is probable that, if the cost of Vanadium is reduced, it will be much more largely used.

The present price of the metal Vanadium is high, and, consequently, its use in steel manufacture is limited to high-class steels required for special purposes; but the small quantities in which it is used should enable Vanadium steel to compete, as regards price, with Nickel steels containing from 3 to 4 per cent. of Nickel.

High-speed Tool Steel.—During the last fifteen years great improvements have been made in the manufacture and heat treatment of tool steels, as the result of which cutting speeds are now used which appeared to be impossible a few years ago. These improvements depend mainly on the properties induced by the addition of special ferro-alloys, such as Tungsten, Chromium, Molybdenum, and Vanadium.

The following table, taken from an article by Professor Carpenter, gives the compositions of four types of tool steels, with comparative figures of their speed of cutting medium hard steel:—

TABLE XCVIII.

Make of Steel.	C.	Si.	Mn.	W.	Cr.	V.	Speed per Minute in Feet.
	Per cent.	Per cent.	Per cent.	Per cent.	Per cent.	Per cent.	
Jessop Carbon, . .	1·047	0·206	0·19	..	0·207	..	16
Mushet self-hardening, .	2·15	1·044	1·58	5·44	0·40	..	26
Taylor-White, . .	1·85	0·150	0·30	8·00	3·80	..	60
Modern high-speed steel, .	0·67	0·043	0·11	18·91	5·47	0·29	100

The increase in cutting speed above noted is due to variation in composition and almost equally due to improvements in heat treatment.

The Carbon steels as mainly used for tool purposes up to the year 1894 contained only small quantities of constituents other than iron and Carbon; the Mushet self-hardening or air-hardening steels, which began to come into general use about 1894, contained considerable amounts of Tungsten besides high Carbon, Silicon, and Manganese. The original Taylor-White tool steel, which may be considered to have introduced rapid cutting tools, contained larger quantities of Tungsten and Chromium with high Carbon.

and low Silicon and Manganese. The modern high-speed tool steel consists essentially of an Iron-Tungsten-Chromium alloy with medium Carbon (0·6), and in some cases a small amount of Vanadium; Molybdenum is sometimes used to replace some of the Tungsten. The most suitable heat treatment of these steels differs greatly from that of Carbon steels, for whereas in hardening the Carbon and Mushet tools the greatest care had to be taken not to overheat them, the Taylor-White and modern rapid tool steels cannot be overheated, in order to get the full cutting value of them, they have to be almost melted. For the manufacture of high-speed tool steel, the materials which must be of the highest quality are melted in crucibles. Each crucible takes a charge of 80 to 50 lbs., according to the number of times it has previously been used; after melting, the charge is either teemed into a ladle, which receives the contents of several crucibles and then into an ingot mould, or direct into the mould. After solidification, the ingot is stripped and cropped as usual.

The steel is so hard in the cast condition that it has to be softened previously to being worked by a prolonged heating at a temperature of about 800° C. in a gas-heated furnace. This last treatment being continued sometimes for two days. At the end of this treatment the ingot is ready for forging. For this purpose it is heated to about 1,000° C. in a clear coke fire, and then forged to the required size, and sometimes rolled as a finishing operation. The material then undergoes a second annealing at about 800° C. for from 12 to 18 hours, according to its section, and is then again heated to 1,000° C., and forged to any desired shape. When cold it is ground on a dry stone or dry emery wheel. It is now ready for the high-heat treatment, for which it is heated in a smith's fire until the nose begins to melt, and is then completely cooled in an air blast, or in some cases, after the temperature has fallen to 900° C., it is oil-quenched. In some cases the tool also receives a low-heat treatment at a temperature of 625° C.