CHAPTER XVI.

THE INFLUENCE OF SILICON, SULPHUR, PHOSPHORUS, MANGANESE, ARSENIC, COPPER, TIN, ANTIMONY, ETC., ON THE PHYSICAL PROPERTIES OF STEEL.

As the effects of the different impurities in steel vary very considerably with the percentage of Carbon present, we shall first discuss their influence on mild or structural steel containing ·25 per cent. or less of Carbon, and, in the second place, shall consider how their presence influences the properties of the higher Carbon steels. The questions involved are by no means easy of solution, as, although a large number of experiments have been made by different experimenters, by the addition of known quantities of impurities to different varieties of steel, and most important comparative results have been obtained, it by no means follows that the same amount of impurity present would have the same influence on steel made by a different process, even if the other constituents, as determined by analysis, gave the same results. Again, the temperatures of casting, reheating, and rolling, and the amount of work put upon the material, all have considerable influence, and make it unsafe to draw too sweeping generalisations from experiments on a small scale. The costliness of experimenting with large quantities of steel has, with few exceptions, been prohibitive of direct investigations, and consequently we have largely to rely upon results obtained with small ingots. Undoubtedly a great amount of most useful information has been obtained in this way, which, if it cannot be regarded as yielding absolute results, has almost invariably indicated, within reasonable limits, the influence the special impurity would be likely to exert upon the material made under ordinary commercial conditions. The question of the influence of any one particular element on what may be regarded as pure steel is, however, an extremely easy one compared to the question, which has to be faced every day in actual practice, as to what will be its influence when four or five other variables are present, some intensifying and some diminishing the effects due to the particular element under consideration. The tendency amongst engineers is to get over the difficulty by insisting upon a material as free as possible from every constituent other than the Carbon required to produce the requisite hardness, and sufficient Manganese to prevent red shortness. This is without question the right course to take, and there is only one objection to it, and that is, that such material is costly when manufactured on a commercial scale. Except in cases of very high-priced tool steel, steel generally contains more impurities than are theoretically desirable, although there have been great improvements made in this respect during the last few years. The reduced cost of pig-iron and improvements in Siemens practice, both acid and basic, especially the latter, have enabled an extremely pure material to be made, with the greatest regularity, at a cost considerably below that of a comparatively impure material a few years ago.

We will first of all consider the influence of each constituent *per se*, and then discuss the more intricate question of the combined influence of a number of impurities.

The Influence of Silicon on Mild or Low Carbon Steel.

Silicon forms solid solutions with iron, probably as **FeSi**. The constitution of Silicon steels * is practically independent of the amount of Carbon present,

* Guillet, *Iron and Steel Inst. Journ.*, 1906, vol. ii., p. 14.

being pearlitic with less than 5 per cent. of Silicon, consisting of pearlite and graphite between 5 and 7 per cent., and containing graphite only with more than 7 per cent. of Silicon.

Silicon was for a long time, and is still by some metallurgists, regarded as having very injurious effects upon the properties of steel, being credited with producing both brittleness and red shortness; but an examination of the facts, especially in the light of recent experiments certainly does not support these contentions. Over twenty years ago Mrazek, as the result of a set of experiments, came to the conclusion that Silicon, within reasonable limits, had very little influence on the strength, hardness, or brittleness of steel, and that it did not produce red shortness. The systematic experiments of Messrs. Turner and Hadfield most strongly confirm these views, although the latter found that the presence of above ·7 of Silicon was fatal to welding. Professor Turner's * first experiments were made by adding varying quantities of Silicon pig to almost Carbonless steel, obtained from a Bessemer basic blow *before the addition* of Ferro-Manganese, and practically all the samples containing above ·15 per cent. were extremely red short, owing, in the author's opinion, to the more or less over-oxidised nature of the steel; Prof. Turner attributes the red shortness to the Silica and slag formed in the steel by the Silicon reacting with the Oxygen present. The next set of experiments by Professor Turner were made in exactly the same manner from finished basic Bessemer steel, but *after the addition* of the Ferro-Manganese, the content of Silicon varying from ·01 to ·5 per cent. These bars did not show the slightest red shortness at any temperature between a low red and a welding heat, proving, almost without doubt, that the red shortness in the earlier experiments was due to over-oxidised metal rather than to the Silicon present in the alloys. The author can himself vouch for the freedom from red shortness of the second set of bars, as they were tested by plating and welding, under his own supervision, at the works of the Staffordshire Steel Company, Bilston. Table xlix. gives details of mechanical tests and chemical analyses. After making allowances for the variations in the other impurities present, there is practically no increase in maximum stress or in the elastic limit, and no decrease of the reduction of area or elongation until over ·315 per cent. of Silicon is present; and, in fact, only a slight increase in the maximum stress and elastic limit, with corresponding decrease in the extension and reduction of area, becomes perceptible with ·38 Silicon. Even when the Silicon reaches ·5 per cent. there is an increase of only 7 tons in the maximum stress, and a loss of 4 per cent. on the extension in 10 inches.

In 1889 Hadfield † published the results of a most exhaustive series of experiments on the influence of Silicon on mild steel. Taking up the investigation from the point at which Professor Turner had left it, he made a series of alloys from ·7 to 8·8 per cent. In Table lxx. are given the principal mechanical results obtained by Hadfield. The one bar which showed any sign of red shortness up to 5·53 per cent. of Silicon was the first, with only ·24 per cent Si, but this fact is accounted for by the very low content (·14 per cent.) of Manganese and the somewhat high percentage of Sulphur, and, in view of the other results, cannot be considered to be in any way connected with the Silicon present. We cannot do better than give a summary of the conclusions Hadfield draws from his own experiments as to the influence of Silicon on steel, both in the forged and cast condition.

* *Journ. Chem. Soc.*, 1887, p. 129.
† *Iron and Steel Inst. Journ.*, 1889, vol. ii., p. 222.

TABLE LXIX.—PROFESSOR TURNER'S EXPERIMENTS ON THE INFLUENCE OF SILICON ON MILD STEEL.*

Number of Sample.	Chemical Analysis. Silicon per cent.	Carbon per cent.	Sulphur per cent.	Phosphorus per cent.	Manganese per cent.	Works Tests. Rolling.	Hot.	Cold.	Welding.	Mechanical Tests. Limit of Elasticity. Tons per Sq. Inch.	Limit of Elasticity. Lbs. per Sq. Inch.	Maximum Stress. Tons per Sq. Inch.	Maximum Stress. Lbs. per Sq. Inch.	Ratio of Limit to Break.	Extension per cent. on 10 In.	Reduction of Area per cent.	Work done per Cubic Inch.	Relative Hardness.
																	Tons.	
1	0·010	0·16	0·050	0·060	0·550	Rolled well.	Good.	Perfect.	Perfect.	22·00	...	29·64	...	0·743	23·1	48·8	6·25	Differences so small as to be scarcely perceptible.
2	0·061	0·16	0·028	0·058	0·619	,,	,,	,,	,,	22·21	...	31·61	...	0·703	20·4	40·7	5·80	
3	0·070	0·15	0·084	0·051	0·500	,,	,,	Good.	,,	21·05	...	29·51	...	0·713	22·9	51·5	6·12	
4	0·092	0·21	0·084	0·064	0·634	,,	,,	Perfect.	,,	22·43	...	33·66	...	0·666	19·4	44·1	5·82	
5	0·102	0·18	0·028	0·066	0·662	,,	,,	Good.	,,	21·26	...	33·57	...	0·634	20·6	51·4	6·06	
6	0·121	0·19	0·064	0·068	0·576	,,	Good, but rather red short at welding heat.	,,	Fair.	22·70	...	31·86	...	0·712	21·9	43·7	6·31	
7	0·135	0·13	0·028	0·057	0·480	,,	Good.	,,	Perfect.	21·29	...	29·42	...	0·724	24·8	56·6	6·62	
8	0·247	0·19	0·028	0·074	0·642	,,	,,	,,	,,	22·23	...	34·70	...	0·640	17·6	49·6	5·36	
9	0·320	0·15	0·040	0·081	0·490	,,	,,	,,	,,	22·32	...	33·23	...	0·671	16·7	36·1	4·96	
10	0·382	0·16	0·042	0·087	0·533	,,	,,	Perfect.	,,	24·72	...	35·67	...	0·693	18·0	30·7	5·79	
11	0·504	0·18	0·094	0·121	0·455	,,	,,	Broke short at 50°.	,,	26·35	...	36·72	...	0·717	19·4	34·8	6·45	

* Report of Committee appointed by the British Association, 1888.

ADFIELD'S SILICON EXPERIMENTS.

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ing on Area. bs. per quare nch.	Total Extension per cent.	Reduction of Area per cent.	Bending Test of Annealed Bars, ⅜ inch wide by ¼ inch thick.	Remarks.
3,920	30·05	54·54	.. ..	Samples A to D bent double cold, like dead soft steel, and afterwards flattened close without breaking.
6,000	37·55	60·74	(1) Bent double cold. (2) Bent cold through 180°; radius ⅜ inch, perfect.	
2,506	16·90	42·70	.. ..	
6,160	29·50	54·54	.. ..	This test bar had a black oxidised surface at fracture quite unwelded.
6,080	34·02	52·66	(1) Bent double cold. (2) Bent through 180°; radius ⅜ inch, perfect.	
3,840	25·45	42·56	.. ..	
1,578	26·50	66·40	.. ..	
2,880	31·10	50·58	.. ..	
3,920	35·10	54·52	(1) Bent double cold. (2) Bent through 180°; radius ⅜ inch, perfect.	
2,800	24·30	58·30	.. ..	
,480	18·48	28·02	.. ..	
,160	36·50	59·96	(1) Bent double cold. (2) Bent through 180°; radius inch, perfect.	
,665	5·60	..	.. ..	
,200	17·60	24·36	.. ..	
,680	6·05	6·64	(1) Bent double, but broke in radius with last blow. (2) Bent through 180°, but broke off sharp at bend.	
,885	2·50	..	.. ..	
,400	11·10	14·22	.. ..	
,360	8·85	9·28	(1) Bent only to right angle; much stiffer. (2) Broke at 45°.	
541	3·20	5·65	.. ..	
760	·004	·20	.. ..	
120	·64	·98	(1) Very brittle; would not bend at all. (2) Broke at 15°.	
	..	..	.. ..	Specimen "G" was not quite straight and snapped across the middle with a blow from a hammer while being "set" by the workman. It was evidently very brittle.
520	·30	·70	.. ..	
000	·37	Broke in thread.	(1) Very brittle; would not bend at all. (2) Snapped in three pieces at first blow of hammer.	
315	·70	1·98	.. ..	Test bar broke simultaneously in two places, so that a piece 5 inches long from middle flew right out. This piece itself was nearly separated in two parts by a crack.
	..	..	.. ..	
	..	..	.. ..	

TABLE LXIX.—PROFESSOR TURNER'S EXPERIMENTS ON THE INFLUENCE OF SILICON ON MILD STEEL.*

TABLE LXX.—HADFIELD'S SILICON EXPERIMENTS.

Mark.	Analysis. Carbon per cent.	Silicon per cent.	Sulphur per cent.	Phosphorus per cent.	Manganese per cent.	How Ingot Forged.	Whether Tested in Annealed or Unannealed Condition.	Limit of Elasticity. Tons per Square Inch.	Lbs. per Square Inch.	Breaking Load on Original Area. Tons per Sq. Inch.	Lbs. per Square Inch.	Total Extension per cent.	Reduction of Area per cent.	Bending Test of Annealed Bars, $\frac{1}{2}$ inch wide by $\frac{1}{4}$ inch thick.	Remarks.
A	·14	·24	·08	·05	·14	Fairly well.	..	..	..	..	..	..	..	.. ..	Samples A to D bent double cold, like dead soft steel, and afterwards flattened close without breaking.
A	..	·18	..	..	..	..	Unannealed.	22·00	49,280	33·00	73,920	30·05	54·54	.. ..	
A	..	·20	..	..	..	..	Annealed.	15·17	33,980	25·00	56,000	37·55	60·74	(1) Bent double cold. (2) Bent cold through 180°; radius $\frac{3}{8}$ inch, perfect.	
A	..	..	..	..	..	..	"	15·17	33,980	23·44	52,506	16·90	42·70	.. ..	This test bar had a black oxidised surface at fracture quite unwelded.
B	·18	·79	..	..	·21	Very well.	..	..	..	..	..	..	..	.. ..	
B	..	·70	..	..	..	..	Unannealed.	25·00	56,000	34·00	76,160	29·50	54·54	.. ..	
B	..	·73	..	..	..	..	Annealed.	19·00	42,560	29 50	66,080	34·02	52·66	(1) Bent double cold. (2) Bent through 180°; radius $\frac{3}{8}$ inch, perfect.	
B	..	·87	..	..	..	..	"	19·00	42,560	28·50	63,840	25·45	42·56	.. ..	
B	..	..	..	..	..	..	..	18·16	40,678	27·49	61,578	26 50	66·40	.. ..	
C	·19	1·60	..	..	·28	Very well.	..	..	..	..	..	..	..	.. ..	
C	..	1·60	..	..	..	..	Unannealed.	28·00	62,720	37·50	82,880	31·10	50·58	.. ..	
C	..	1·52	..	..	..	..	Annealed.	25·00	56,000	33·00	73,920	35·10	54·52	(1) Bent double cold. (2) Bent through 180°; radius $\frac{3}{8}$ inch, perfect.	
C	..	..	..	..	..	..	..	23·09	51,722	32·50	72,800	24·30	58·30	.. ..	
D	·20	2·18	·06	·04	·25	Very well.	..	..	..	..	..	..	..	.. ..	
D	..	2·11	..	..	..	..	Unannealed.	31·00	69,440	39·50	88,480	18·48	28·02	.. ..	
D	..	2·13	..	.	..	..	Annealed.	25·50	57,120	34·00	76,160	36·50	59·96	(1) Bent double cold. (2) Bent through 180°; radius inch, perfect.	
D	..	..	..	..	..	..	..	20·22	45,293	27·98	62,665	5·60	..	.. ..	
E	·20	2·67	..	..	·25	Very well.	..	..	..	..	..	..	..	.. ..	
E	..	2·69	..	..	..	..	Unannealed.	32·00	71,680	42·50	95,200	17·60	24·36	.. ..	
E	..	2·67	..	..	..	..	Annealed.	24·00	53,760	32·00	71,680	6·05	6·64	(1) Bent double, but broke in radius with last blow. (2) Bent through 180°, but broke off sharp at bend.	
E	..	..	..	..	..	..	..	23·50	52,640	28·52	63,885	2·50	..	.. ..	
F	·21	3·46	..	..	·29	Very well.	..	..	..	..	..	..	..	.. ..	
F	..	3·39	..	..	..	..	Unannealed.	35·00	78,400	47·50	106,400	11·10	14·22	.. ..	
F	..	3·36	..	..	..	..	Annealed.	30·00	67,200	39·00	87,360	8·85	9·28	(1) Bent only to right angle; much stiffer. (2) Broke at 45°.	
F	..	..	..	..	..	..	..	29·45	65,968	34·17	76,541	3·20	5·65	.. ..	
G	·25	4·49	..	..	·36	Very well.	..	..	..	..	..	..	..	.. ..	
G	..	4·18	..	..	..	..	Unannealed.	45·00	100,800	49·00	109,760	·004	·20	.. ..	
G	..	4·23	..	..	..	..	Annealed.	None visible.	..	38·00	85,120	·64	·98	(1) Very brittle; would not bend at all. (2) Broke at 15°.	
G	..	..	..	..	..	..	..	..	..	..	..	..	..	.. ..	Specimen "G" was not quite straight and snapped across the middle with a blow from a hammer while being "set" by the workman. It was evidently very brittle.
H	·26	5·53	·06	·04	·29	Very well.	..	..	..	..	..	..	..	.. ..	
H	..	4·9	..	..	..	..	Unannealed.	None visible.	..	48·00	107,520	·30	·70	.. ..	
H	..	4·8	..	..	..	..	Annealed.	25·00	56,000	25·00	56,000	·37	Broke in thread.	(1) Very brittle; would not bend at all. (2) Snapped in three pieces at first blow of hammer.	
H	..	..	..	..	..	..	..	None visible.	..	38·98	87,315	·70	1·98	.. ..	Test bar broke simultaneously in two places, so that a piece 5 inches long from middle flew right out. This piece itself was nearly separated in two parts by a crack.
I	·04	7·23	..	..	·29	..	..	No test, bar made would not forge.				..	..	.. ..	
J	·08	8·83	·07	·05	·68	..	..	"	"	"		..	..	.. ..	

1. *Forged Condition.*—"The forge reports that the material, A (Table lxx.) (·24 per cent. Si), did not forge well, cracking somewhat when hammered, but all the other samples, B to H (·79 to 5·53 per cent. Si), when forged at a fair yellow heat, required no special care, thus clearly showing that Silicon, even up to as high as about 6 per cent., does not destroy the malleability of the metal. Upon, however, exceeding this percentage the material is red short, crumbles at a low heat, and, notwithstanding the low percentage of carbon present (·25 per cent.), becomes really a species of cast iron. It should be noted that, if the carbon had been higher, the point at which malleability ceases would have been with a much lower percentage of Silicon. Such red shortness is not removed by the addition of Manganese."

"It may also be mentioned that no return of strength, as is so specially characteristic of Manganese steel, takes place on a further addition of Silicon. Any further addition merely increases its resemblance to silicious cast iron. Nor do gradually increasing percentages, as in the case of Manganese steel, destroy the magnetic properties of the alloy, a 7 per cent. material being apparently as susceptible as ordinary iron or steel drillings."

"Apparently Silicon, up to 1·5 or 1·75 per cent., added to iron, although increasing the limit of elasticity and raising the tensile strength, does not impair ductility, but after this the further increase of tensile strength noticed, is only obtained with a serious loss of ductility. There seems to be no sharp line of demarcation, but, after exceeding 1·5 to 2 per cent., further slight increases cause great changes in the characteristics of the material. In this respect, therefore, its action rather resembles that of Carbon in contradistinction to the action of Manganese, of which larger amounts are required to effect similar changes."

"The annealed flat bending pieces, ½-inch wide by ¼-inch thick, gave good results, specimens A, B, C, and D (·24 to 2·18 per cent. Si) bending double cold without fracture, more like soft steel, and after being bent double the pieces were flattened close together cold without showing signs of fracture. Specimen E (2·67 per cent. Si) also bent double cold, but broke in the radius with the last blow. F (3·46 per cent. Si) was much stiffer, bending only to a right angle. G and H (4·49 and 5·53 per cent.) would not bend, and were exceedingly brittle. These bending tests were confirmed by Professor Turner with bars of the same size. Up to D specimen the samples bent to an angle of 180°, with ½-inch radius. Pieces from the bars used for bending tests were also tested for weldability, but entirely without success."

As regards water quenching or hardening, samples A to D (·24 to 2·18 per cent. Si) were unhardened by quenching from even the highest temperature. When plunged at welding heat into specially cold water no hardening beyond a surface stiffening took place, nor was their toughness impaired. Specimen E (2·67 per cent. Si) was heated to a yellow heat and plunged into water at 70° F. This piece was much stiffened, but broke only on being bent double. Another piece, heated to welding heat and quenched in water at 52°, gave a similar result. Sample F (3·46 per cent. Si) was merely stiffened by the same treatment, and was just as brittle as before and had not hardened. In respect to being toughened by water quenching, this material differs from Manganese steel. The heating produced but little alteration in fracture, the crystallisation being still open and coarse. H (5·53 per cent.) quenched both at an ordinary and at a welding heat was merely skin-hardened. These tests clearly prove that Silicon does not confer the same property as Carbon does upon iron—*i.e.*, of becoming hardened when quenched from a high temperature in a cooling medium.

The whole of the samples were subjected even to a welding temperature without falling to pieces.

2. *Cast State.*—As might be expected, the whole of the samples were very free from honeycombs, but this soundness was only acquired at the expense of toughness or ductility. Silicon steel pipes or settles, to a much greater extent than ordinary steel, and this in itself is a considerable disadvantage. Its fluidity, when being poured, is less than that of ordinary steel. The crystallisation or form of fracture of the lower percentages resembles ordinary mild cast steel, but above 2·5 per cent. Si the crystals become very large and glazed, and cleave somewhat after the nature of spiegeleisen. As this large and marked crystallisation increases, the material becomes extremely brittle, and, on further additions, its appearance approaches Silicon pig-iron, and is non-malleable. Considerable shrinkage is caused by high percentage of Silicon in cast or unforged material, but at the same time increase in soundness is obtained.

As in the forged, so in the cast material, when the Silicon exceeds about 2 per cent., and the peculiar crystallisation commences, neither annealing nor water cooling seems to affect the structure.

Taking Hadfield and Turner's experiments together, we may safely conclude that Silicon, when present to a much greater extent than is usually found in mild steel, has no injurious effects on the physical properties. There is one point, however, which must be borne in mind, and that is, that unless specially added, Silicon rarely, if ever, exceeds 0·100 in mild steel which has been carefully manufactured. Its presence in much larger proportion, occasionally, in the case of Bessemer steel points to the fact that, during its manufacture, the "critical temperature" was reached at which the Carbon is oxidised before the Silicon; that it was evidently a "hot blow," and, consequently, the steel was cast at too high a temperature. High Silicon steel made under these conditions is always very unreliable, and this may be one possible explanation why Silicon obtained, and still to a great extent retains, its bad reputation. In cases of the failure of such steels, the high content of Silicon has been considered the cause, whereas the real cause has been careless manipulation during manufacture, high Silicon content being only one of the results.

Hadfield's conclusion that Silicon is prejudicial to welding must be taken as referring to steels with ·7 per cent. and more, and it will not be surprising if such high percentage of Silicon does have a bad influence in this respect, although results obtained by other experimenters with alloys containing several percentages of Silicon have differed from Hadfield as regards the influence of Silicon on welding.

Both Professor Turner's experiments and a great deal of evidence produced by Professor Howe are, moreover, fairly conclusive that much higher percentages than are commercially met with in mild steel do not appreciably affect the welding properties of the metal. Silicon is generally supposed to increase the fusibility of steel, although to a smaller extent than the same percentage of Carbon, and it is possible that it does lower the melting point; but even if this is so, Hadfield found that fluidity, as distinct from fusibility, was decreased instead of increased as might have been anticipated.

Barrett and Brown * examined the Silicon steels made by Hadfield, and found that with an addition of 2·25 to 2·5 per cent. Silicon magnetic permeabilities excelling those of pure iron were obtained. C. F. Burgess and J. Aston † have examined the effect of Silicon on electrolytic iron, and concluded that there is no general improvement in permeability due to the presence of Silicon, but they confirm the experience of practice that a high Silicon alloy, after annealing at high temperatures, is of high permeability for low magnetising forces and densities, such as are used in transformer design. They suggest that in the Silicon steels containing 3 to 6 per cent. Silicon, used in transformer work, the heat treatment is of importance comparable with that of Silicon content. Silicon increases very considerably the electrical resistance of steel, and this is also of considerable importance in transformer working, as it reduces the eddy-current loss.

The Influence of Silicon on Medium and High Carbon Steels.

We have not any results of systematic investigations, like those of Hadfield on mild steel, to guide us in forming a definite conclusion as to the influence of Silicon on the strength, ductility, etc., of high Carbon steel, and have largely to depend upon the experience of different metallurgists and engineers; but it may be broadly assumed that the higher the Carbon the more the influence of Silicon becomes apparent, although even in high Carbon steels the ductility appears to be influenced only to a comparatively small extent. It is of vital importance that tires, for instance, should not show, under the very severe stresses to which they are subjected, the least tendency to brittleness, and steels with from ·2 to ·4 of Silicon and ·5 to ·6 per cent. Carbon have been found to give very satisfactory results. One special brand of tires which has obtained quite a reputation for resistance to wear and general reliability has about this composition, and a special point is made of the Silicon content being from ·3 to ·35 per cent. Professor Howe also gives various analyses of gun steels with from ·2 to ·45 Silicon and ·4 to ·6 per cent. Carbon, which have given good results, and which necessarily have been subjected to shock and very great stress. C. P. Sandberg has experimented with Silicon in steel rails, and has met with considerable success. In their manufacture, he removes the Silicon from the iron as completely as possible, and then adds a known quantity in the form of high-percentage Silico-spiegel or Ferro-Silicon, in this way the percentage of Silicon is easily regulated, and the wearing properties of the steel are found to be greatly improved, this being largely due to the complete removal of gases and Oxide from the steel. Sandberg finds that Silicon up to ·35 per cent. gives good results. With regard to crucible steel for tools, an important and interesting investigation was carried out by Dr. F. C. G. Muller,‡ from which he concluded that Silicon to the extent of ·8 had no deleterious influence upon the quality of crucible tool steel, and suggested that ·5 or ·6 per cent. of Silicon might actually improve the quality.

Without, however, going so far as this, we may safely say that Silicon for some special Carbon steels is not only not prejudicial, but in certain cases may be beneficial, and in the case of tool steels has no bad effects when present far in excess of that found in ordinary commercial crucible steel. Certain spring steels contain ·45 per cent. Carbon, and up to 2 per cent. Silicon.

* *Journ. Inst. Elect. Eng.*, vol. xxxi., p. 675.
† *Met. and Chem. Eng.*, 1910, vol. viii., No. 3, p 131.
‡ *Stahl und Eisen*, vol. vii., pp. 375-377.

The Influence of Sulphur.

The influence of Sulphur on the tensile strength and ductility is so slight up to ·1 per cent. that, for all practical purposes, its direct action may be disregarded. Webster * credits Sulphur with increasing the tensile strength 500 lbs. per square inch for every increment of ·01 per cent., but the evidence he adduces hardly warrants this conclusion, and he himself admits that the question requires further investigation. The injurious effects of Sulphur, however, are seen during the rolling, a very small percentage causing considerable red shortness, which is noticeable by the ingots or bars cracking at the edges. The amount of Sulphur which may be present without being perceptible during rolling or welding varies with the process by which the steel has been made, the amount of Manganese and copper present, and the temperature of casting. Manganese masks the effects of Sulphur; the higher the percentage of Manganese for a given content of Sulphur, the less the tendency to red shortness. Copper has been credited with acting exactly in the opposite direction, but the experiments of Messrs. Stead and Evans † seem to show definitely that there is no scientific foundation for this belief. For steel required for welding and general structural work, Sulphur should never exceed ·06 per cent., although no signs of red shortness may be apparent when ·1 or even more is present in certain steels. Although, as has been pointed out, Sulphur has apparently no direct influence in the cold on the strength or brittleness of steel, and by some experimenters is even stated to increase its toughness, the real danger of using a high Sulphur steel for structural purposes, even when it has not in any way to be worked hot, lies in the fact that, during rolling, numerous cracks are liable to develop, which close up, and are quite imperceptible in the finished material. Nevertheless these remain as flaws, and may form starting-points for rupture when the material is subjected to any sudden stress. Thus the contention that, provided the steel is not to be worked hot after it leaves the rolling mill, the percentage of Sulphur is of little or no importance, so long as the bars or plates are free from all visible defects, cannot be admitted for one moment, and probably material of this description is one of the most dangerous that can be employed by the engineer, the more so, that the tensile strength and ductility, as evidenced by elongation and reduction of area, will give no indications, in the majority of cases, that the material is in any way untrustworthy. In the author's opinion, many of the so-called mysterious failures are due to the original material having been slightly red short during the rolling. Starting with fairly good materials, with careful treatment manufacturers should have no difficulty in producing regularly a steel with about ·06 per cent., and certainly ·08 per cent. is the very maximum that should be allowed in any steel, either for rails or structural purposes. In high Carbon steel, the effect of Sulphur at high temperatures seems to be quite as marked as with mild steel or even more so, but it is rarely present in such large proportion as in the case of mild steel, partly owing to the fact, which has been clearly established, that Carbon in excess has a tendency to expel Sulphur,‡ but still more to the very careful selection of the extremely pure materials used

* *Iron and Steel Inst. Journ.*, 1904, vol. i., p 331. † *Ibid.*, 1901, vol. i., pp. 89-100.

‡ Howe (*Metallurgy of Steel*, p. 50) cites instances where, by cementation, Sulphur has been reduced from ·055 to ·019 and from ·04 to ·02, and Percy's experiments were quite conclusive that fusion with excess of Carbon very greatly reduced the Sulphur in cast iron.

in the manufacture of high Carbon and especially of crucible steel. In the case of the latter also, there is less danger of absorption of Sulphur from furnace gases, such as exists in the case of Siemens steel, and which is frequently the cause of a very appreciable increase in Sulphur during the conversion of the pig iron into steel.

Sulphur is almost certainly present in more than one form in steel, as it is well known to all metallurgical chemists that, on dissolving some steels in dilute acids, practically all the Sulphur present is evolved in the form of Sulphuretted Hydrogen, whilst others give up only a portion under these conditions, a small percentage being retained in the insoluble residue. No relation, however, has been shown to exist between these two conditions and the physical properties of the steel.

Professor Arnold * first pointed out that the microscope showed that Sulphide of iron exists in steel as (1) globules or ovoids, (2) thin irregular oval laminæ, (3) cell-walls presenting in section a mesh-like appearance, the latter being by far the most dangerous form; Sulphide of Manganese, on the other hand, nearly always occurs as globules or ovoids, very rarely as meshes. An investigation by Prof. Le Chatelier† showed that when Sulphide of iron occurs as meshes surrounding the grains of iron, the addition of Manganese breaks up these meshes into globules, probably owing to the formation of Sulphide of Manganese. As Sulphide of iron has a lower melting point than the welding temperature of steel, on heating a high Sulphur steel, the grains in part become surrounded by a more or less semi-fluid Sulphide of iron, which to a great extent explains why such steels are red short. The addition of Manganese breaks up the meshes of Sulphide of iron, and probably replaces them by globules of Sulphide of Manganese, which have a higher melting point. This is Prof. Le Chatelier's rational explanation of the action of Manganese in removing or reducing the red shortness in steel induced by Sulphur. Sulphide of Manganese, although undoubtedly far less injurious than Sulphide of iron, may, however, very seriously affect the physical properties of the material if present in considerable quantities, and especially if aggregated together in patches. These patches are liable to form starting points for cracks which may ultimately develop into fractures under stress.

According to Levy, Manganese Sulphide is seldom free from Ferrous Sulphide, even when the steel contains a considerable amount of Manganese, as these two compounds are mutually soluble in the solid state.

Many instances are well known of high Sulphur material in rails and other finished sections having given good results over many years of service, and such material on being subjected to drop testing has stood remarkably well; but, in those cases which have come under the author's observation, the Manganese has always been fairly high. On the other hand, such material not infrequently fails under sudden shock, owing, in all probability, to the incipient cracks developed during hot working, which have never completely welded up. There is no doubt that the temperature of rolling has a very important influence on the final mechanical properties of such material in the finished state, and until we are able to adjust the percentage of Manganese in proportion to the Sulphur present, and to control the temperature of rolling so as to insure freedom from these incipient flaws, the only safe course

* *Metallographist*, vol. iii., p. 273, 1900. The author greatly regrets that by an oversight this paper of Prof. Arnold's was not referred to in the first edition.

† *Bulletin de la Société d'Encouragement*, September, 1902.

for engineers appears to be to insist upon being supplied with low Sulphur material. Steel containing relatively large percentages of Sulphur appears, as might be expected, to corrode more rapidly than low Sulphur steel.

The Influence of Phosphorus.

Of all impurities usually present in steel practical experience has established the fact that Phosphorus is the one that most prejudicially influences the physical properties of the metal by producing brittleness under shock, and general cold shortness. Opinions have been somewhat divided as to its effect on rolling and hot working generally, but it is now generally admitted that this is practically nil when not more than ·2 per cent. is present. Howe * refers to numerous metallurgists who, as the result of practical experience, have found that up to ·8 or 1 per cent. the influence of Phosphorus is not perceptible during rolling, although others have professed to be able to detect its effects when ·25 to ·3 per cent. is present. The author's experience is that up to ·25 it does not give any indication of its presence in the rolling mill in the case of mild steel, and he has frequently forged under the hammer metal containing 1 to 1·5 per cent. Phosphorus, taken from the basic Bessemer converter during the afterblow, without its showing the least sign of red shortness, although cold it was so brittle that a blow with a small hand hammer would break a ½-inch square rod. For practical commercial purposes, however, Phosphorus in steel should not exceed ·08, and all are agreed that under ·1 per cent. does not affect the rolling properties. If ·1 per cent. or over is present, it tends, however, to produce a finished metal with coarse crystallisation, and low temperature of rolling, slowness of cooling after rolling, and the size of section, etc., have considerable influence in this respect.

The tensile strength may be very slightly increased by small increments of Phosphorus, but between ·05 and ·1 the elongation and reduction of area does not appear to be affected. Campbell † gives a large number of results of mechanical tests on steel angles of the same thickness, containing from ·05 to ·1 of Phosphorus, which show no difference in the elongation or reduction of area; he concludes that small increments of Phosphorus, from ·04 to ·1, cannot be detected in the ordinary testing machine, a conclusion which agrees with the author's own experience. This is a matter of great importance to the engineer, who frequently relies almost entirely upon his mechanical tests, especially upon the reduction of area and elongation, to determine the fitness or unfitness of a material for a given purpose, and it cannot be too strongly insisted upon that a material which may give most satisfactory results in every respect in the testing machine may be high in Phosphorus, and prove highly dangerous when subjected to sudden shock. Cold bending tests with a falling weight (not in a press) are probably among the most practical tests for high phosphoric material, but here again we find the influence of Phosphorus is very capricious, some extraordinarily good results being obtained with material which would be distinctly dangerous, to say the least, for use in structural work. Probably the heat treatment, especially the temperature of rolling and rate of cooling, has very important influence on the ductility of phosphoric steel, and there is very considerable evidence to show that continued, although slight, vibration tends to induce a change in the structure of the metal which renders it quite unfit to resist the application of a sudden shock or stress.

* *Metallurgy of Steel*, p. 73.
† *Manufacture and Properties of Structural Steel*, p. 471, 2nd edition.

Dr. Stead read two valuable papers on Iron, Carbon, and Phosphorus before the Iron and Steel Institute in 1900 and 1915, which will well repay careful perusal, and the latter paper contains a valuable bibliography on the subject. In discussing the eighth report of the Alloys Research Committee,* the same author gave some results of tests on the influence of Phosphorus on the mechanical properties of Carbon steels. For these tests the specimens were prepared by taking a ladle of normal steel and adding successive amounts of Phosphorus. The specimens thus obtained each contained 0·3 per cent. Carbon and 0·04, 0·30, and 0·50 per cent. of Phosphorus respectively.

The following are the results of the tensile tests carried out on the bars :—

Phosphorus. Per cent.	Yield Point. Tons per Sq. Inch.	Maximum Stress. Tons per Sq. Inch.	Elongation on 6 Ins. Per cent.	Reduction of Area. Per cent.
0·04	20·4	33·1	23·0	52·0
0·30	25·4	39·9	23·0	45·3
0·50	32·0	44·2	20·0	45·3

Alternating-strain tests carried out by Professor Arnold on bars of these specimens $\frac{3}{8}$ inch square with 660 alternations per minute, showed that with 0·04 per cent. Phosphorus 271 reversals were required to fracture, with 0·3 Phosphorus 200 reversals, and with 0·5 Phosphorus 100 reversals only. Slow alternating bend tests on pieces $\frac{3}{8}$ inch by $\frac{3}{16}$ inch by 3 inches required 605, 446, and 150 reversals respectively through an angle of 30° to cause fracture.

These results indicate that the addition of Phosphorus raises the yield point and the maximum stress, at the same time reducing the elongation and contraction of area, and rendering the steel more brittle. From a consideration of the tensile tests alone, any engineer would have been justified in accepting this material, although it is well known that steel containing 0·3 and 0·5 per cent. of Phosphorus is unsafe.

In view of what may be called the treacherousness of phosphoric steel, it is difficult to fix a definite limit for the maximum content of Phosphorus which can be safely allowed, but there can be no doubt that the lower this is, the safer the material, and for structural purposes ·06 per cent. is quite as much as can be accepted with a feeling of security. In steel rails ·08 per cent. of Phosphorus may be permitted with safety.

In the case of higher Carbon steels the influence of Phosphorus is much more marked than in low Carbon steels, and Howe † considers that an increase of ·01 per cent. may be detected in 1 per cent. Carbon steel. In the best qualities of crucible steel only the very purest materials are used, the Phosphorus being frequently under ·01 per cent., and it is stated by more than one authority that an increase of ·005 per cent. has a distinct effect on the wearing properties of the cutting edges of tools. In a report to the United States Board on testing iron, the smith's ‡ results showed that out of eighteen samples of tool steels tested there were only three with over ·03 per cent. Phosphorus, and these gave the worst results, as measured by a comparison of the weight of shavings turned, etc., without regrinding the tool, although one with ·025 per cent. gave very good results. The noted Dannemora steel is particularly free from Phosphorus.

* *Proceedings Inst Mech. Engineers*, 1907, p. 308. † *Metallurgy of Steel*, p. 69.
‡ Report U.S. Board on the Testing of Iron, &c., 1881, vol. ii., p. 592.

The Influence of Manganese.

In considering the influence of this metal on steel it must be remembered that, unlike most of the other constituents, it is not an impurity originally present which the metallurgical treatment has failed to remove, but is, at all events in the case of all steel used for structural purposes, an essential constituent especially added to deoxidise the decarburised metal so as to prevent its being red short. Manganese in excess of that required to combine with Sulphur, combines with a portion of Carbon to form Mn_3C, which is found associated with the Fe_3C present. The effect which Manganese has upon the tenacity and ductility varies very considerably with the percentage of Carbon in the steel, its influence being much more marked in the case of high than of low Carbon steels. In the author's opinion, for mild steel and rail steel, the less Manganese a steel contains above that required to insure solid ingots and freedom from red shortness the better, and, provided that good pig-iron free from sulphur is used, and reasonable care taken during the manufacture, there should not be the slightest difficulty in obtaining these results with ·4 to ·5 per cent. of Manganese in the finished product, at all events for mild steel made in the Siemens furnace. In the case of rails which are still very largely made by the Bessemer process, it is difficult, owing to the large additions necessary to obtain the required content of Carbon, to keep the Manganese down to this limit, and provided it does not exceed ·8 per cent., the metal may be expected to give good results. The general tendency of Manganese is undoubtedly to increase the tensile strength and somewhat to reduce the ductility, but neither of these effects is nearly so great as has often been maintained by many metallurgists, and a slight increase in Carbon, or other constituents accompanying the Manganese, is very often responsible for a greater part of the increase, and for the very varying results obtained. The fact that many thousands of axles and tires are made every year with 1 per cent. of Manganese shows that, up to this point, it does not reduce the ductility so as to induce brittleness to any dangerous extent, as, notwithstanding the severe stresses that such material is subjected to, failures are comparatively rare. It must be borne in mind, however, that both axle and tire steels are made from very high-class material most carefully selected, and the greatest care is taken during manufacture to insure the uniformity of composition of the finished material. In the case of mild steel required for boiler plates, and for bridge or other structural work, an increase of Manganese has a very distinct hardening effect, and above ·6 per cent. begins to be dangerous and should not be allowed. The tendency amongst steel makers to bring up the tensile strength to the specification by increasing the Manganese, instead of the Carbon, is greatly to be deprecated, and notwithstanding the reported excellent records of mild steel plates with 1 per cent. of Manganese, and steel rails containing more than this amount engineers will be well advised to decline to accept such material. Webster,* from a large series of test bars, came to the conclusion that, in the case of mild steel, the effect per unit of Manganese on the tensile strength decreased as the percentage of Manganese increased, and whereas an increase from ·25 to ·3 per cent. of Manganese raised the tensile 1,000 lbs. per square inch, an increase from ·55 to ·6 raised the tensile only 500 lbs. This may be so, and probably 1,000 lbs. per square inch increase for every $\frac{1}{10}$ per cent. Manganese is not far from the truth, although other experimenters have

* *Iron and Steel Inst. Journ.*, 1894, vol. i, p. 331.

found less, and Campbell * gives a series of tests showing that the addition of ·2 per cent. of Manganese does not appreciably affect the tensile strength.

The influence of Manganese on high Carbon steels required for tools is much more marked, and if present in any quantity it is very liable to cause fracture on quenching. The highest class tool steel rarely contains more than ·3, and frequently less, and although numerous instances are on record where steels with ·4 and ·5 of Manganese have given excellent results, it is decidedly safer to keep the Manganese low, and there is no reason, even from a manufacturer's point of view, for having a high Manganese in such steels. The influence of large percentages of Manganese—viz., from 2 per cent. and upwards—will be dealt with under the head of special steels.

The Influence of Arsenic.

In 1888, Mr. A. E. Tucker and the author † made a series of experiments on the effect of Arsenic on mild steel, and came to the conclusion that up to ·17 it had no effect upon the ductility or tenacity of the steel, and that elongation and reduction of area were likewise unaffected, but that above this limit cold shortness was slightly noticeable and gradually increased. It was also found that, up to 1 per cent., Arsenic produced no red shortness at rolling temperatures, but that, above ·17 per cent., the influence on welding was distinctly marked, and above ·25 per cent. the steel refused to weld. In 1895, Stead,‡ after a most exhaustive investigation, practically confirmed these results. He sums up his results as follows:—That between ·1 and ·15 per cent. of Arsenic in steel for structural purposes has no material effect on mechanical properties, such as tenacity, ductility, etc., as shown by bending and tensile tests, but that its influence is just noticeable with ·2 per cent. The rolling and forging properties are not affected in the slightest degree by considerable percentages of Arsenic, but welding is made more difficult by even very small quantities. The only points where Mr. Stead's results disagreed with those of Mr. Tucker and the author were in the quenched samples, in which Mr. Stead found that the arsenical steel bent better after quenching than before. This is a point which requires further investigation, as Professor Arnold's tests show that quenching had a distinctly hardening effect. Mr. Stead found the influence of large quantities of Arsenic to be less than was indicated by earlier experiments, and, as his were far more exhaustive, he is probably correct in this respect. In any case, Arsenic in such proportion as it is usually present in commercial steel—*i.e.*, up to ·1 per cent.—is not in any way prejudicial, except when the steel is required for welding.

The Influence of Copper.

The influence of Copper on steel was formerly greatly exaggerated. Whereas it was considered to be very harmful, it is now known, when present in small quantities, to have no serious influence on the physical properties of steel.

According to a statement in Professor Howe's *Metallurgy of Steel*,§ an American firm of steel rail makers habitually made Bessemer T rails with ·51 to ·66 per cent. Copper, and they were so slightly red short that, in spite of their thin flanges and the exceptionally low temperature at which they

* *Struct. Steel*, p. 266.
† *Iron and Steel Inst. Journ.*, 1888, vol. i., p. 183.
‡ *Ibid.*, 1895, vol i., p. 108.
§ *Metallurgy of Steel*, p. 83.