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LXXXIII.—*The Influence of Silicon on the Properties of Cast Iron.* Part II.

By THOMAS TURNER, Assoc. R.S.M. (Demonstrator of Chemistry, Mason College, Birmingham).

THE present paper is a continuation of one recently published (this vol., p. 577) in which an account was given of a series of experiments intended to determine the influence of the regulated and gradual addition of silicon to cast iron of more than usual purity. A description has already been given of the general method of procedure, the composition of the materials used, and the analyses of the metal obtained. Experiments were also described by which the influence upon tensile strength and modulus of elasticity was gradually made clear, and the effect upon the proportion of graphitic carbon shown. A further account, though necessarily incomplete, was also given of the appearance on fracture, the relative fluidity of the melted material, the appearance of the castings, soundness of metal, and resistance to fracture. Other experiments have now to be mentioned in connection with the influence of silicon on the physical and mechanical properties of cast iron.

Specific Gravity.—The specific gravity of the specimens might obviously be determined in two ways: on the one hand by the employment of fragments such as borings or turnings, or on the other by the use of pieces of considerable size. It appeared at first doubtful which of these two methods was to be preferred. It had been already shown that the 10 specimens to be operated upon varied very much in tenacity and hardness, and it therefore appeared probable that their density would be unequally affected by the different forces exerted upon them while being reduced to small fragments. On the other hand, the presence of any unsoundness in the specimen would have a much greater influence upon the result if large masses were employed. Under these circumstances, it was considered best to determine the specific gravity both in a turned piece of considerable size, and in the turnings from the specimen.

For the determination of the specific gravity in mass, it was considered best to employ large pieces all as nearly as possible of one size. For this purpose, cylinders 3 inches long and 1 inch in diameter were prepared, each weighing upwards of 270 grams, whilst their maxmium difference of water displacement did not vary more than $\pm$ 0·06 gram, except in one instance, where the specimen afterwards proved to be unsound. The pieces were washed with alcohol to free

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them from any accidental grease, and suspended by a fine platinum wire in water at 20°.

The turnings produced during the preparation of the cylinders were used for the determination of the specific gravity of fragments. To avoid any mistake, the specimens were served out singly to the workman, and the operation personally superintended throughout, each cylinder being marked, and the turnings labelled, before another specimen was commenced. In the determination itself, a modified Sprengel tube (Nicol, *Phil. Mag.*, June, 1885, 455) was employed, by which considerable weights of metal could be operated upon, 17·5 grams being the least quantity employed. The tubes were filled with paraffin oil, of sp. gr. 0·79215, and immersed in a Nicol's (*Phil. Mag.*, May, 1883, 339) constant temperature bath. In each case where much difference existed between the specific gravity of the cylinder and that of the turnings, duplicate experiments were made, and as these always agreed well together, it is probable that very tolerable accuracy was obtained. The results are given in the following table:—

TABLE C.—*Specific Gravity of Cast Iron at* 20° *C.*
(Water at 20° = 1.)

Silicon per cent.	Sp. gr. of cylinders.	Sp. gr. of turnings.
0·19	7·560	7·719
0·45	7·510	7·670
0·96	7·641	7·630
1·96	7·518	7·350
2·51	7·422	7·388
2·96	7·258	7·279
3·92	7·183	7·218
4·75	7·167	7·170
7·37	7·128	7·138
9·80	6·978	6·924

It will be noticed that there is not generally a very marked difference between the values obtained by the different methods. The turnings from the three strongest specimens, however, show a *diminished* density (compare this vol., p. 580), and this is particularly marked in the middle one of the three, containing 1·96 per cent. Si, which possesses the highest tenacity of the series. On the other hand, the rest of the turnings, with the exception of silicon pig itself, show an *increased* density due to the mechanical force exerted during turning. In the case of the cylinder containing 0·45 per cent. Si, the specimen was afterwards proved to be faulty in the interior, and this evidently accounts for its irregularity.

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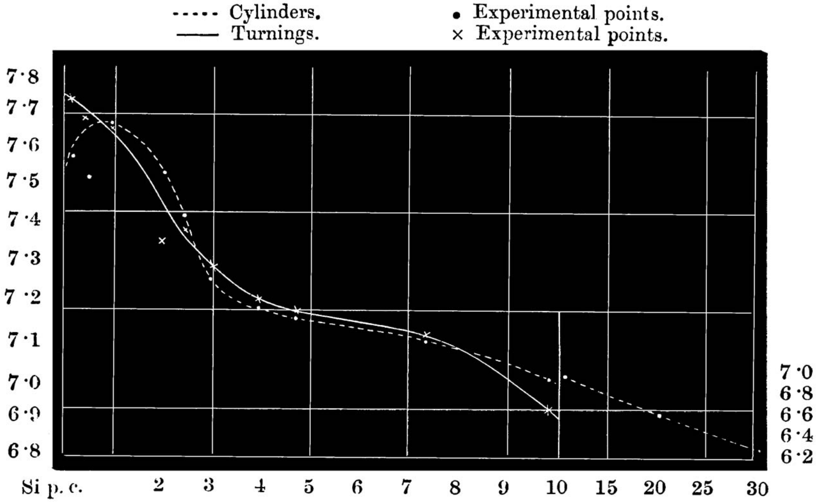
FIG. 3.—SPECIFIC GRAVITY.



In Fig. 3 these facts are expressed graphically, the curve being continued, on a reduced scale, with data obtained from *Watts' Dictionary*, 1st Suppl., p. 753, where an account is given of some silicides of iron prepared by Hahn.

Relative Hardness.—The smooth ends of the cylinders employed in specific gravity experiments were used for the determination of relative hardness. It had been originally intended to do this by means of a weighted steel point, but, on the advice of Dr. Nicol, a cutting diamond was substituted for the steel point. The diamond was firmly fixed, vertically, point downwards, into the end of a long lath, and at right angles to its length. The lath was then balanced in the middle, and fixed so as to allow of free motion in a horizontal plane. The smooth end of the cylinder to be operated upon was brought underneath the diamond, and weights added until a perceptible scratch was produced on drawing the diamond across the surface of the metal. A note was made of the weight which had been added, and this was gradually diminished until no visible scratch was produced on again drawing the diamond over the metallic surface. The difference between the two observations was generally 5 grams, and, on repeating the observation upon the same specimen, the results obtained did not vary from each other by more than the same amount. In observations of this kind, it was not considered necessary to use weights smaller than a gram.

The mean of the two observations was taken as the point desired,

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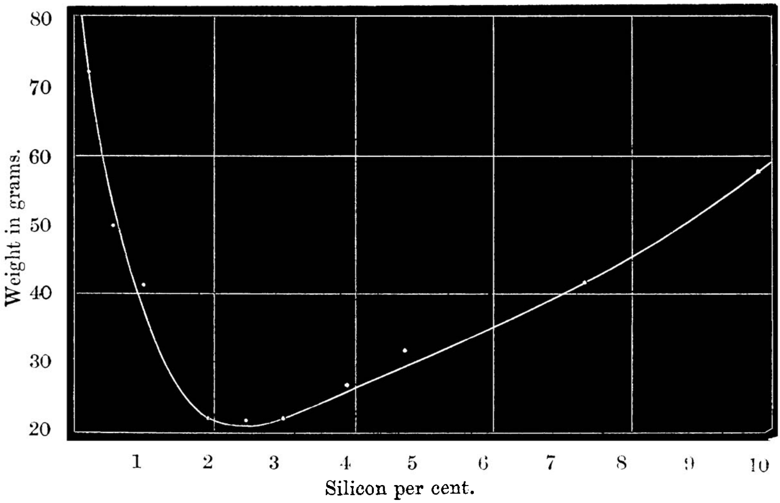
and the results obtained are given in Table D (below). It will be noticed that pure cast iron is the hardest of the whole series, and that the hardness is diminished by the addition of silicon up to 2 per cent. There is then no appreciable difference until 3 per cent. has been added, after which the metal is gradually rendered harder by continued addition of silicon.

TABLE D.—*Relative Hardness.*

Silicon per cent.	Weight in grams.
0·19	72
0·45	52
0·96	42
1·96	22
2·51	22
2·96	22
3·92	27
4·75	32
7·37	42
9·80	57

These results may be graphically represented in a curve, as we have in Fig. 4, when it will be seen that the change produced is gradual and quite regular.

FIG. 4.—RELATIVE HARDNESS.



Working Qualities.—During the preparation of the cylinders pre-

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viously mentioned, especial notice was taken of the working qualities of the iron. The observations were made by an experienced workman, and they agree very nearly with the determinations of hardness given above.

0 per cent. Si. Very hard indeed; rather unsound under the skin, but turned bright.

0·5 per cent. Si. Very hard, though not so hard as the previous specimen; there were several blowholes under the skin, and the specimen proved unsound when tested afterwards.

1 per cent. Si. Hard, though softer than the last specimen; cut well, gave bright surface, and was quite sound.

2 per cent. Si. Good, sound, ordinary, soft cutting iron, of excellent quality; turned surface darker in colour.

2·5 per cent. Si. Rather harder than the last, but otherwise the same.

3 per cent. Si. Like 2 per cent.

4 per cent. Si. Like the latter, but rather harder.

5 per cent. Si. Cuts rather harder than 4 per cent., though not unusually hard.

7·5 per cent. Si. Still harder, and cuts very like the next specimen. The turned surface is not so smooth.

10 per cent. Si. Hard cutting iron, though still much softer than the first specimen (0 per cent.).

The appearance of the turnings is also characteristic. These, at either end of the series, are small and of irregular shape, gradually passing into the longer curly turnings of good cutting iron as they approach the 2—3 per cent. specimens.

Crushing Strength.—For the determination of the crushing strength, it was originally intended to employ the cylinders 3 inches long by 1 inch diameter, which had been used in the specific gravity experiments. But as the specimens were of unusual strength, it was found necessary to reduce the diameter to 0·75 inch. The specimens were tested by Professor A. B. W. Kennedy, at University College, and I have again to express my obligation to him for the kindly interest he has manifested in these experiments. The results obtained are given in Table E (p. 907). The exact composition of each specimen has already been given (this vol., p. 581).

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TABLE E.—*Crushing Strength.* (Tests by Professor Kennedy.)

Silicon per cent.	Breaking load per square inch. Pounds.	Tons.
0	168,700	75·30
0·5	204,800	91·42
1	207,300	92·54
2	* { 135,600	60·53
	139,000	62·05
2·5	172,900	77·18
3	128,700	57·45
4	106,900	47·74
5	103,400	46·16
7·5	111,000	49·55
10	76,380	34·10

These figures illustrate the same fact, before shown in several ways, that on addition of small quantities of silicon the metal improves in quality, but gradually becomes inferior on the addition of larger percentages. This is shown graphically by the curve given in Fig. 5 (p. 908), and for comparison the curves of tensile strength and modulus of elasticity have been drawn to suitable scales, and are given in the same diagram. All three curves show the same general characters, though it will be noticed that the maximum point is different in each case; this difference, however, is not very considerable.

It will be observed that only six of the experimental results, or two-thirds of the whole, agree well with the curve drawn. But it must be remembered that this class of mechanical tests is more liable to variation than most others, errors of $\pm$ 5 per cent. not being uncommon in different specimens of the same material; and, as two of the results are high, and the other two low, there can be little doubt as to the general shape of the curve. This curve must, therefore, be regarded more as indicating a general tendency than as a rigid representation of fact.

In Fig. 6 (p. 909 *et seq.*) we have full-sized sketches of the test pieces after fracture. They are of interest as showing that greatest plasticity is produced by the addition of a moderate amount of silicon, say about 2—3 per cent.

The following remarks were made by Professor Kennedy on the character of the test pieces :—

0 per cent. Surface smooth and silvery along planes of shear, very fine grained, and light in colour where fairly fractured.

* This result, being somewhat irregular, was repeated.

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FIG 5.—EFFECT OF SILICON ON CAST IRON—CRUSHING STRENGTH.

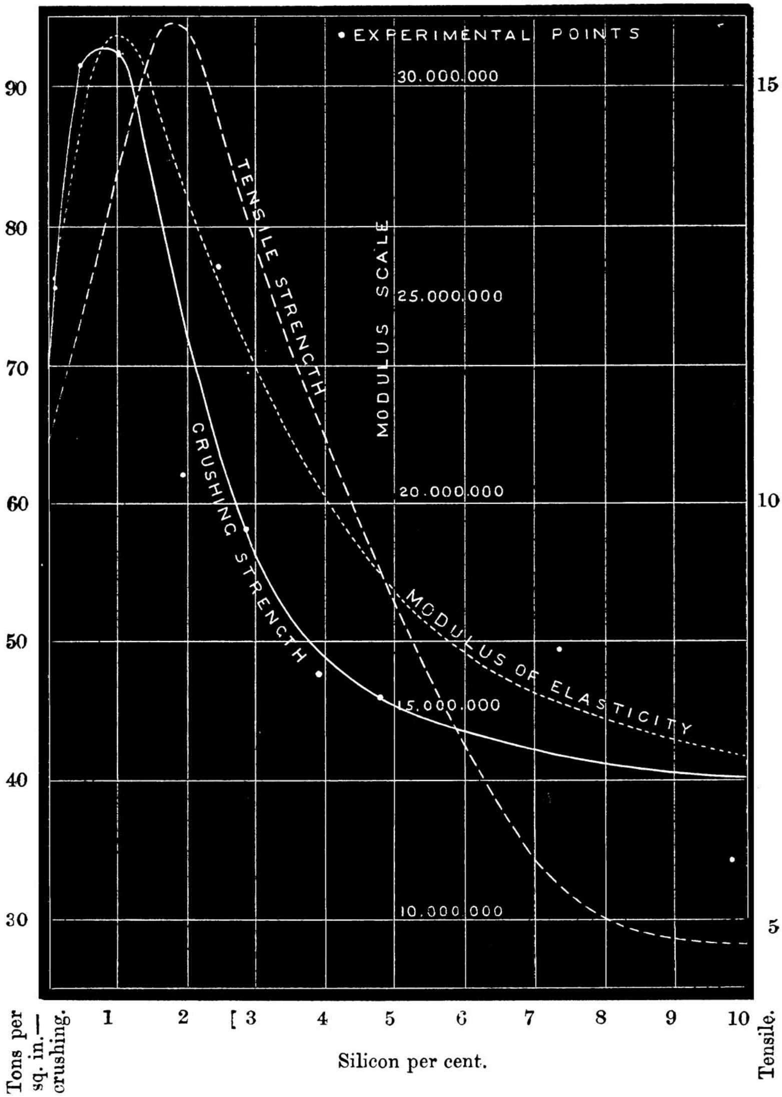

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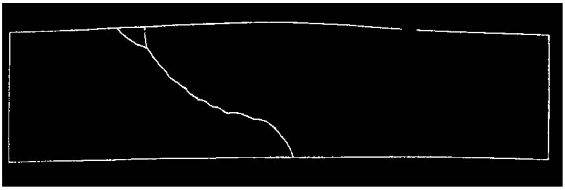
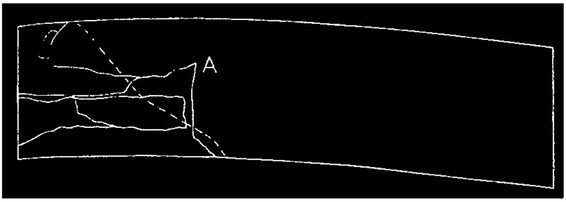
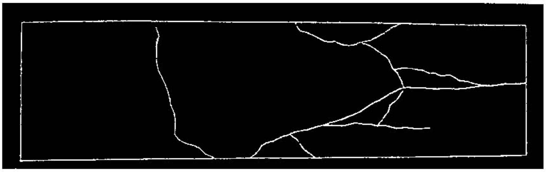
FIG. 6:—FULL-SIZE SKETCHES SHOWING FRACTURES (Professor Kennedy).



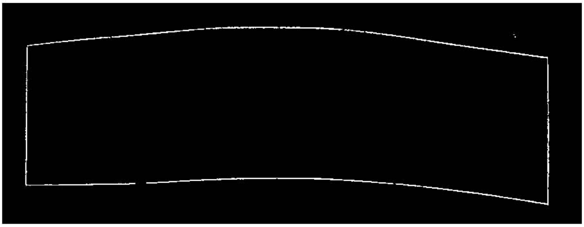
0 per cent. Si.



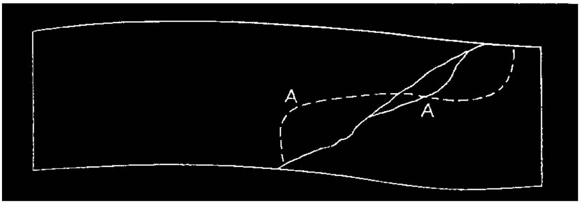
0·5 per cent. Si.



1 per cent. Si.



2 per cent. Si.



2 per cent. Si.

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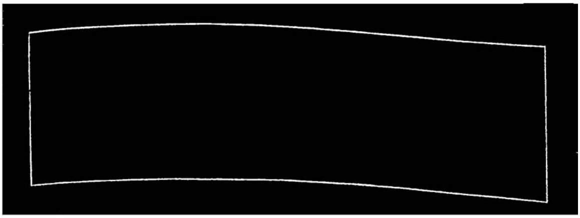
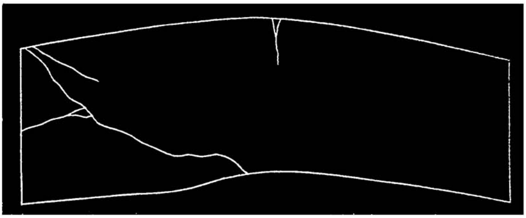
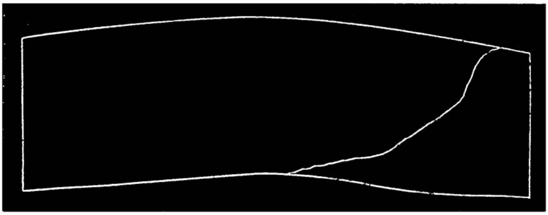


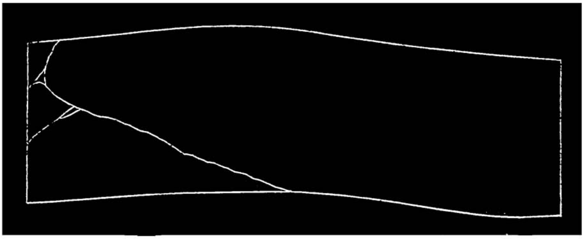
2·5 per cent. Si.



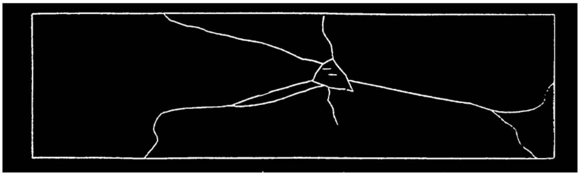
3 per cent. Si.



4 per cent. Si.



5 per cent. Si.



7·5 per cent. Si.

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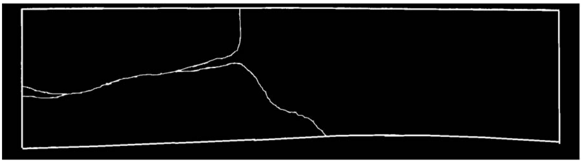

10 per cent. Si.

0·5 per cent. In greatest part silvery, but at A close grained grey crystals.

1 per cent. Very irregular, in part split longitudinally, part transversely, showing planes smooth and silvery. Direct fracture as in sketch.

2 per cent. Silvery grey; at AA close grained grey crystals.

2·5 per cent. Very slightly distressed on surface.

3 per cent. Surface silvery along shearing planes.

4 per cent. Do. do.

5 per cent. Do. do.

7·5 per cent. Light grey, broken very irregularly, sound.

10 per cent. Light grey, fairly crystalline, irregular in texture, not quite sound.

Before leaving this part of the subject, it may be well to refer to what has been urged as an objection to the results brought forward in this paper, namely, that they are in most cases exceptionally high. This is illustrated in the following table:—

	Author.	Woolwich, 1858.	Fairbairn, 1853.
Tensile—			
Maximum ..	15·70 tons.	14·05 tons.	—
Minimum ..	4·75 ,,	4·85 ,,	—
Crushing—			
Maximum ..	92·54 ,,	58·42 ,,	95·9 tons.
Minimum ..	34·10 ,,	22·54 ,,	40·7 ,,
Specific gravity—			
Maximum ..	7·719 ,,	7·268 ,,	7·530 ,,
Minimum ..	6·924 ,,	6·886 ,,	6·771 ,,

In the second column are the results obtained at Woolwich in experiments conducted upon a large number of British irons, and published in the report "Cast Iron Experiments, 1858," p. 155. My attention was called to this report by Mr. John Spiller in June last, and I am obliged to him for introducing me to the most complete and interesting experiments on this subject with which I am acquainted. It is my intention shortly to refer to these results in a separate paper, when I hope to show that they furnish strong support of my own

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observations. It is necessary to explain how it was that these important experiments were previously overlooked. It is true that they are quoted in various text-books, including *Watts' Dictionary* and Percy's "Iron and Steel." But in every case, so far as I am aware, the analyses and the mechanical tests were separately referred to, and, only recently being able to obtain access to the report itself, I had no reason to connect the mechanical tests recorded in one place with the chemical analyses published in another.

In considering the objection previously mentioned, however, it must be remembered that special care was taken in my experiments to prepare iron unusually free from the ordinary impurities, and that the carbon is always uniformly low for cast iron. Hence we should naturally expect the maximum results to be somewhat higher than usual. There would be more force in the objection if the results had been *lower* than usual, since then the tests might have been considered untrustworthy; in the present instance, however, such a supposition is evidently quite out of the question.

If now the various curves which have been given in this paper be examined the following conclusions may be drawn:—

1. That a suitable small addition of silicon to the cast iron previously almost entirely free from silicon is capable of producing a considerable improvement in the mechanical properties of the metal.

2. That the amounts of silicon capable of producing the maximum increase are probably as follows:—

For crushing strength	about	0·80	per cent.
,, modulus of elasticity........	,,	1·00	,,
,, specific gravity (in mass)....	,,	1·00	,,
,, tensile strength............	,,	1·80	,,
,, softness and working qualities	,,	2·50	,,

3. That in cast iron where general strength is required the amount of silicon should not vary much from about 1·4 per cent.; but that when special softness and fluidity are required about 2·5 per cent. may be added. Even in the latter case, however, any increase beyond 3 per cent. must be dangerous.

In connection, however, with the above statements, it must be remembered that any considerable quantity of other elements, besides carbon and silicon, will materially affect the properties of the metal, and probably also the amount of silicon which should be present, in order to produce any desired character. The results are only strictly true under the circumstances of my experiments, and a careful comparison of the results of a large number of observations upon different kinds of iron will be necessary before the conclusions drawn may be

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considered absolutely trustworthy. Upon this work, I am at present engaged.

At the Glasgow meeting of the Iron and Steel Institute in September last, an interesting paper was read by Mr. Charles Wood, in which it was shown that by a suitable addition of siliceous pig iron to Cleveland iron, castings of softer character could be obtained. Mr. Wood also showed that by adding silicon to white cast iron the metal passed gradually into soft grey iron with increased tenacity, thus confirming the results given in my previous paper. The addition of siliceous iron was carried on during several months' working, running 60 to 70 tons per day, and satisfactory results were obtained. Mr. Wood recommends that for castings where strength is required the silicon should be about 1·8 to 2·0 per cent., while for soft, sharp, clean castings about 2·6 to 3 per cent. of silicon is preferred. These numbers are in each case about $\frac{1}{2}$ per cent. higher than those deduced from my experiments, and the difference probably depends upon the phosphorus present in Cleveland iron.

Since my paper was written I have received the following note from Mr. Wood :—

"I am still using silicon pig largely in the foundry, and since reading my paper have sold several lots to different founders, who speak very favourably of the softening effect. I think myself, on further experiments, that my percentages are rather high. For strong iron 1·5 to 1·75 per cent. would be nearer, whilst 2·5 to 2·75 might be taken for softness, although 3·00 will do no harm, as in many classes of castings softness is of greater importance than a slight decrease of strength."

I may now perhaps be allowed to say a few words as to the cause of the changes which silicon produces when added to pure cast iron.

It has long been observed that certain kinds of grey iron, when quickly cooled, may be hardened, their specific gravity increased, and their character changed, from grey to white. On the other hand, certain white irons when strongly heated, and afterwards allowed to solidify slowly, become converted into grey iron, which, on account of its greater liquidity and softness, is preferred for many purposes. But it has been shown by Dr. Percy ("Iron and Steel," p. 117) that certain kinds of grey iron cannot be rendered white by chilling; and this fact is confirmed by Ledebur; on the other hand, Percy was unable to change some kinds of white iron into grey, even by a very high temperature and subsequent slow cooling (p. 121). Hence though in the majority of cases the question of white or grey iron may be settled by the circumstances of temperature and rate of cooling, yet in other instances it depends on chemical constitution, and the character of the metal can only be changed by altering the chemical

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composition. Irons which are permanently white are rich in manganese or sulphur, but deficient in silicon, whilst irons that are permanently grey are probably rich in silicon and poor in manganese and sulphur. Thus No. 1 dark grey iron, which is highly graphitic and generally also rather highly siliceous, is found to be quite unsuitable for the production of chilled castings, whilst the iron which is found most suitable for this purpose is "strong," usually No. 4 or 5, and contains either a relatively small proportion of silicon, or a large proportion of manganese or sulphur. If we examine into the relationship between temperature and composition, we find that a high temperature, which is found to be necessary for the production of a graphitic iron, is also the most suitable for the reduction of silicon; whilst, on the other hand, the low temperature necessary for the production of white iron lowers the amount of silicon but favours the absorption of sulphur.* It would seem, therefore, that the character of the iron depends not on the temperature alone, but also on those chemical changes which accompany the alteration of temperature.

In this connection I have examined the composition of more than 180 specimens of pig iron, as shown by analysis, a few of which are original, but the great majority have been selected from the works of Percy, Abel, Lowthian Bell, and others. The lowest percentage of silicon found in a specimen of British grey pig iron is 0·81, whilst the highest percentage of silicon in any specimen of white iron, not containing an abnormal quantity of either sulphur or manganese, is under 1 per cent. It must be mentioned, however, that in the case of foreign irons this difference is not quite so plainly marked; and further, that analyses performed 30 years ago or upwards have been rejected, as possibly misleading; whilst some doubtful cases have also been omitted in which the analyses were more or less incomplete. It is not contended that the rule has no exceptions; but it is believed that the general fact has been proved, without the slightest doubt, in the case of British irons. Now, as no other constituent varies in the same manner as silicon has been shown to do, we are justified in concluding that the effect noticed is due, in great part, to a difference in the proportion of silicon present. It has even been stated, on the authority of Karsten and others, that in castings of grey iron the outer chilled portion contains more carbon and less silicon than the inner grey portions.

I do not contend that this explanation of the cause of the difference of the method of occurrence of carbon in cast iron is new. On the contrary, reference has already been made to the observation of Sefström, mentioned by Dr. Percy, "that the carbon in grey iron, in which much silicon exists, say from 2 to 3 per cent., is wholly or

* I. Lowthian Bell. "Iron and Steel," p. 416.

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nearly so, in the graphitic state." And, 30 years ago, Messrs. Price and Nicholson at the works of the Lilleshall Iron Company, were producing iron by a patent process in which grey iron of good chemical quality was melted with the product of the finery forge in proportions regulated by the applications the product was to receive (No. 2618, November 20th, 1855).

In spite of these facts, and others of a similar kind, the close connection between the percentage of silicon and the mode of occurrence of carbon, did not appear to be understood. It is, however, very plainly seen in the two series of experiments conducted respectively by Mr. Wood and myself; although it must be borne in mind that our conclusions are only true when manganese and sulphur are present in but small quantity, and when also the circumstances of temperature and rate of cooling are as far as possible uniform in the different specimens examined.

These questions have been referred to at greater length on account of the interest attaching to the explanation of the results obtained in these experiments. Thus, at the Glasgow meeting of the Iron and Steel Institute, in September last, very considerable difference of opinion was manifested with regard to the question of the influence of silicon on the properties of cast iron. The opinion was expressed, and pretty generally endorsed, that "silicon or glazed pigs were always bad and unreliable, whatever they were mixed with," and that "as to silicon in pig iron itself the less that could be had the better." On the other hand, Mr. Stead agreed "that the less silicon they had in casting the better, provided that, practically, in the casting they kept the carbon in the graphitic condition." And he has kindly expressed his opinion for me as follows: "The strongest iron useful for general foundry purposes is that which contains sufficient silicon to prevent too large a proportion of the carbon remaining in the combined state in the iron when solidified."

I do not think there can be much doubt as to the truth of the result stated in the latter opinion of Mr. Stead, for not only does it agree with the deductions drawn from the experiments mentioned in the earlier part of this paper, but every practical man knows that the strongest iron is a close-grained grey, and one therefore which nearly approaches the limits of grey iron in the direction of mottled or white. But at the same time, in the present state of our knowledge, it appears unreasonable to attribute the whole effect to the action of silicon in rendering the carbon graphitic. What the action of silicon may be, when added to pure iron, in small but gradually increasing quantities, we do not know; and, after numerous attempts to solve this question, I must confess myself no further advanced than when I first began. It appears much more reasonable to suppose the results

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we have noticed as the sum of two influences, namely, that of silicon upon iron itself, combined with its influence in the production of graphitic carbon, than to assume that the whole effect is due to the latter cause alone. Hitherto we have no experimental evidence to support the view that "silicon is always bad" in its effects on cast iron. On the contrary, there is much evidence of an opposite nature, quite apart from that furnished by my own experiments, for it is notorious that "refined metal," which is of special chemical purity and contains only a few tenths per cent. of silicon, is quite unsuitable for foundry purposes, being deficient in tensile strength, too hard for working, and often unsound.

Further, although we find that, in the presence of silicon, a low percentage of combined carbon always accompanies a strong iron, we do not find that the strongest iron has the *lowest* combined carbon, as we should expect if the result were due merely to the separation of graphite. This is illustrated both in the analyses by Mr. Stead, and also in those I have previously given (this vol., p. 581). Again, on examining Fig. 5 (p. 908) it will be seen that the effect produced by the addition of silicon is regular and progressive. We find that up to 1 per cent. the improvement is quite obvious alike in crushing strength, modulus of elasticity, and tensile strength, though this improvement is *not* accompanied by the separation of graphite; between 1 and 2 per cent. we have the strongest iron, accompanied by much graphitic carbon; with upwards of 2 per cent. we have inferior iron, though the gradual deterioration in quality is not accompanied by any regular increase in combined carbon; on the other hand, this distinctly decreases in quantity as the metal becomes weaker. Or, to state the matter in another form, if the effect noticed is wholly due to the separation of graphite, then the percentages of graphite, if expressed in a curve, should be of the same general shape as those curves we have given in Fig. 5; as this is not the case, we are justified in concluding that the separation of graphite is but a part of the effect produced by silicon, and not the whole effect. It is therefore probable that the improvement in the mechanical properties of cast iron, produced by the addition of silicon, is owing partly to a direct beneficial effect due to suitable proportions of silicon itself, and partly to a secondary influence which silicon exerts on the carbon present.

In conclusion, it may be added that I hope shortly to be able to bring forward evidence based upon the researches of Fairbairn, Abel, and others, to support the conclusions I have already drawn, and to show how far the results given in this paper are confirmed, or modified, by the teaching derived from the study of a large number of independent and most carefully conducted experiments.