The Growth of Grey Cast Iron : Third Report

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The Growth of Grey Cast Iron.
(Third Report.)

By Hiroshi Sawamura.

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Synopsis.

The present investigation was carried out to make clear the relation between the growth of grey cast iron due to the abnormal expansion at Ar transformation and that due to oxidation. The various kinds of dilatometer were used for this purpose. According to the author's results, when grey cast iron is repeatedly heated at a high temperature in air, growth takes place principally due to oxidation and growth of this kind is much larger than that due to the abnormal expansion at Ar transformation.

It is acceptable that grey cast iron becomes susceptible to oxidation by passing through its Ar critical range, hence its growth is accelerated by oxidation. But the author cannot agree with the investigators who believe that the abnormal expansion at Ar transformation is a direct cause of growth in every case, the effect of oxidation being indirect.

Introduction.

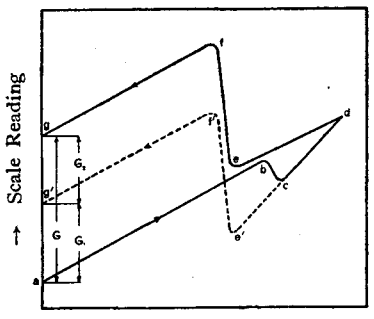
Among many theories on the growth of grey cast iron at high temperature hitherto put forth, the Rugan and Carpenter's oxidation theory[1] is generally accepted as the most reliable at present.

According to this theory, when grey cast iron is repeatedly heated at a high temperature in oxidizing atmosphere, iron oxides and silica are formed in the interior of the iron due to oxidation, giving rise to the permanent expansion of the iron, as these oxides are greater in specific volume than the original metal itself.

In 1922[2] and 1935[3], Kikuta published a new theory based on the experimental fact that grey cast iron expands abnormally at Ar transformation and this expansion is greater in magnitude than the contraction taking place at Ac transformation. His theory may be briefly explained as follows.

Suppose that the change in length of grey cast iron be measured with Honda's dilatometer in oxidizing atmosphere. Assuming the graphitization of the cementite does not occur during heating, the expansion curve will be found as shown in Fig. 1, where the curves **bc** and **ef** represent respectively the contraction at Ac transformation and the expansion at Ar transformation. As the curves **fg** and **ab** are to be parallel each other, the permanent growth of the specimen amounts to **G** on the scale after the first cooling.

Fig. 1.



The first cause for this growth is the fact that the expansion at Ar transformation is greater than the contraction at Ac transformation. The second cause will be found in the fact that the coefficient of expansion of the specimen during heating above Ac_1 point is greater than its coefficient of contraction during cooling from the highest heating temperature to Ar_1 point. The latter phenomenon is explained as being due to the action of oxidation products, filling the internal cracks and cavities of the iron, as obstacles to the free contraction of the iron.

Now, if the interior of the iron is not oxidised, the curve **de** will coincide with the curve **dc**, and the length of the specimen will change along the curve **a b c d e' f' g'**. Hence,

$\mathbf{G} = \mathbf{G}_1 + \mathbf{G}_2$, where $\mathbf{G}_1$ and $\mathbf{G}_2$ represent respectively the magnitude of the growth due to the first and second causes above mentioned. As the heating of the iron is repeated, the combined effect of these two causes appears and the iron grows successively. In conclusion, Kikuta says that the second cause is indirect and less important than the first one.

Benedicks and Löfquist[4] agreed that the abnormal change in volume at Ar transformation is a very important factor for the growth. They insist furthermore that the internal burstings are formed even when the iron passes through Ac_1 point and that the final cause of the growth be attributed to the oxidation of the iron which becomes increasingly porous as it is repeatedly heated.

1) Rugan and Carpenter: Jour. Ir. St. Inst., (1909) (No. II) 29
Carpenter: Ditto., (1911) (No. I) 196

2) Sci. Rept. Tohoku Imp. Univ., 9 (1922) 1

3) Tetsu-to-Hagane, 20 (1935) 591

4) Jour. Ir. St. Inst., (1927) (No. 1) 603

Examining the results of experiments of many investigators, Piwowarsky[5] describes in his work as follows.

At the first heating, a great part of the growth should be due to the graphitization of the cementite. The repetition of heating makes the iron porous and susceptible to oxidation as explained by Kikuta and Benedicks and Löfquist. The oxidation of the iron accompanies a considerable growth.

The theories above referred to indicate that there exists an intimate relation between the growth due to the abnormal change in volume at Ar transformation and that due to oxidation. It has, however, not been throughly investigated yet as far as the author knows. Accordingly, which is greater and which is more important in industry of these two kinds of growth remains uncertain.

In the present paper, the results of experiments carried out on this problem are reported.

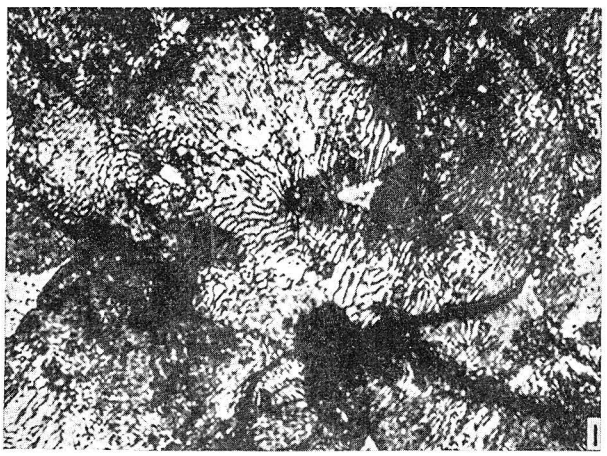
Specimen and description of the experiments.

In the present experiments, "vacuum—[6]", "gas—[7]" and "air-dilatometer[8]" were adopted. The measurement of specific gravity, the experiments with Honda's thermo-balance and microscopic examinations were also carried out as they were required.

The specimens for these dilatometers, 8 m.m. in diameter and 80 m.m. in length, were prepared from sand cast bars, about 40 m.m. in diameter and about 300 m.m. in length. The matrix in their structure is all pearlite as shown in Photo. 1, containing no free ferrite and cementite. Their composition is given in Table I.

The method of preparation of the various gases used and their purification was just the same as in

Photo 1. ×500



Specimen A, as cast.

Table I.

Specimen No.		Composition (%)					
		Total C	Combined C	Si	P	Mn	S
Cast iron	A	3.59	0.72	1.89	0.40	0.58	0.065
	B	3.33	0.72	2.12	0.37	0.64	0.064
	C	3.31	0.59	1.95	0.21	0.74	0.067
	D	3.40	0.75	1.97	0.32	0.56	0.078
	E	3.36	0.72	1.83	0.25	0.54	0.065
	F	3.34	0.68	2.22	0.34	0.66	0.071
	G	3.16	0.75	1.87	0.23	0.71	0.074
	H	3.38	0.71	2.11	0.35	0.68	0.072
Steel	J	0.016	—	0.03	0.003	0.04	0.011
	K	0.04	—	3.90	0.014	0.07	0.014

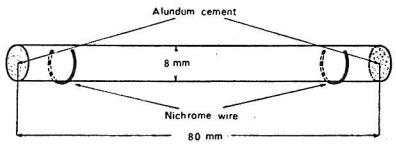
the previous experiments. The heating of the specimen in vacuo was begun after the degree of vacuum had become 10^{-3}–10^{-5} m.m. Hg.

The specimen was pre-heated in many cases before being heated for growth measurement in the following way. As soon as it was heated up to a given temperature in any dilatometer it was cooled down to room temperature without delay at that temperature. The heating and cooling rate of the specimen was about 7°C/min. in many cases.

The growth of the specimen was measured at a given temperature which was kept constant in any dilatometer.

Special care was taken to prevent the specimens from adhering to the dilatometer, as the scale formed on the surface of the specimen is apt to combine with silica at high temperature. For this purpose, a thin layer of alundum cement was stuck to both the end surfaces of the specimen and one round nichrome wire was put on both its ends as shown in Fig. 2 in order not to allow it direct contact with the dilatometer.

Fig. 2.



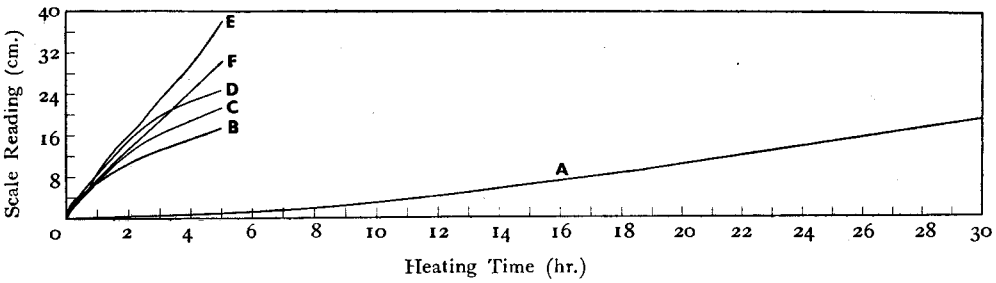
The growth of the specimen in as cast state in air.

Specimen A in as cast state was heated in the air dilatometer up to different high temperatures for the measurement of the growth. The results are shown in Fig. 3.

At 900°C the growth is very small even when it is heated for as long a time as 30 hours.

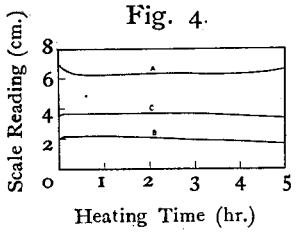
5) Hochwertiger Grauguss, (1929) 321
6) Sci. Rept. Tohoku Imp. Univ. (Prof. K. Honda Anniv. Vol. First Ser.) (1936) 899
7) Sci. Rept. Tohoku Imp. Univ. (Prof. K. Honda Anniv. Vol. First Ser.) (1936) 900
8) Ditto. 903

Fig. 3. (Specimen A.)



A: Specimen in as cast state, heated at 900°C.
B: „ , „ 950°C.
C: „ , „ 980°C.
D: „ , „ 1,000°C.
E: „ , „ 1,050°C.
F: Pre-heated specimen , „ 900°C.

Fig. 4.



A: Specimen J (carbon steel), heated at 950°C.
B: Specimen K (silicon steel), heated at 900°C.
C: Specimen K (silicon steel), heated at 950°C.

It increases, however, as temperature becomes higher.

The specimens of dead soft carbon and silicon steels (Specimen J and K) were also treated in the same condition as in the case of Specimen A. It was found that they do not grow at 900°C and 950°C as shown in Fig. 4.

The same measurement was further carried out on Specimen A which had been previously heated up to 900°C in air. The growth-curve of a thus pre-heated specimen is F in Fig. 3, in which we can confirm that the specimen becomes very susceptible to growth in air when it is pre-heated in the above-mentioned manner.

Though the absolute magnitude of the growth of different specimens is not always the same, the above relative relation exists independently of the kind of specimen.

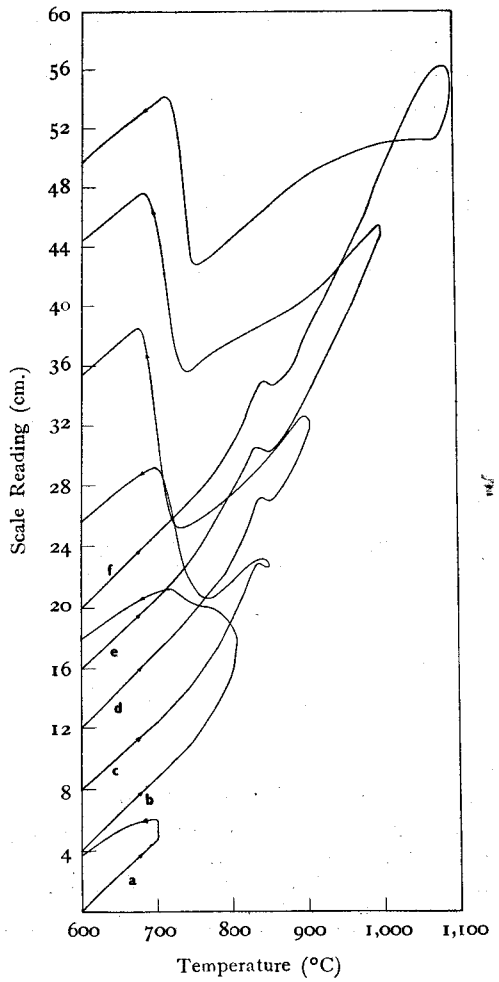
The growth of the pre-heated specimen in air at 900°C.

The growth of the specimen, pre-heated up to different temperatures in vacuo and air.—Specimen B was previously heated up to different pre-determined temperatures in the vacuum and air dilatometers, then heated at 900°C in the air dilatometer for the measurement of growth. Fig. 5 shows the heating and cooling curves during pre-heating in vacuo, those in air being omitted as they are almost similar to the former. The growth of the pre-heated specimen is shown in Fig. 6. The decrease in specific gravity due to the pre-heating and growth was also found as shown in Fig. 7.

At the curve (a) in Fig. 5 little expansion of the specimen is observed, which is due to the error in the temperature measurement of the specimen, but not to graphitization. It may be inferred from Figs. 5 and 7 that the graphitization of pearlite-cementite occurred in the specimen pre-heated up to 805°C. The contraction, found at the curve (f) in Fig. 5 to begin at about 1070°C, will be due to the melting of the steadite.

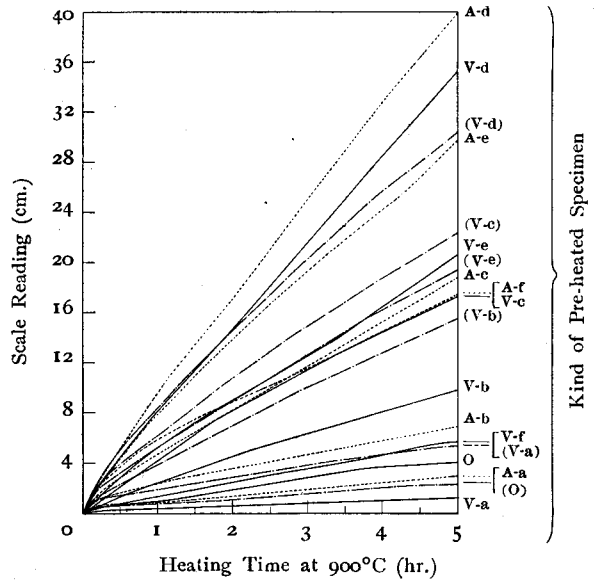
From the results obtained, the fact may be known that the specimens pre-heated up to 700°C grow a little and those pre-heated up to a tem-

Fig. 5. (Specimen B, heated in vacuo.)



a: Heated up to 700°C. b: Heated up to 805°C.
c: „ 850°C. d: „ 900°C.
e: „ 1,000°C. f: „ 1,095°C.

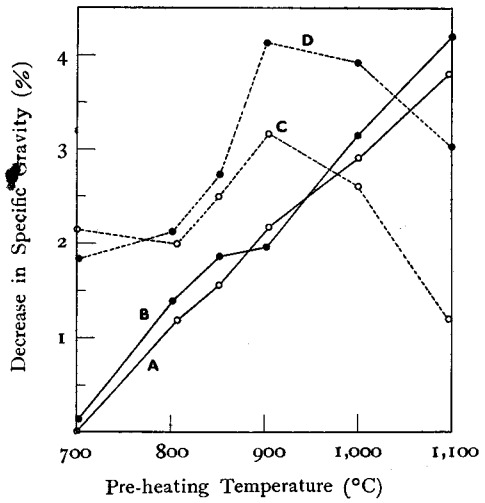
Fig. 6.



Curve No. and Pre-heating Temperature.

Specimen B			Specimen E	
As cast	Heated in vacuo	Heated in air	As cast	Heated in vacuo
O:-	V-a: 700°C	A-a: 700°C	(O):-	(V-a): 700°C
	V-b: 805°C	A-b: 800°C		(V-b): 800°C
	V-c: 850°C	A-c: 850°C		(V-c): 860°C
	V-d: 905°C	A-d: 900°C		(V-d): 920°C
	V-e: 1,000°C	A-e: 1,000°C		(V-e): 1,000°C
	V-f: 1,095°C	A-f: 1,100°C		

Fig. 7. (Specimen B.)



A: After pre-heating in vacuo; for the specific gravity of the specimen in as cast state.

B: After pre-heating in air; for the specific gravity of the specimen in as cast state.

C: After the growth experiment of the specimen pre-heated in vacuo; for the specific gravity of the pre-heated specimen.

D: After the growth experiment of the specimen pre-heated in air; for the specific gravity of the pre-heated specimen.

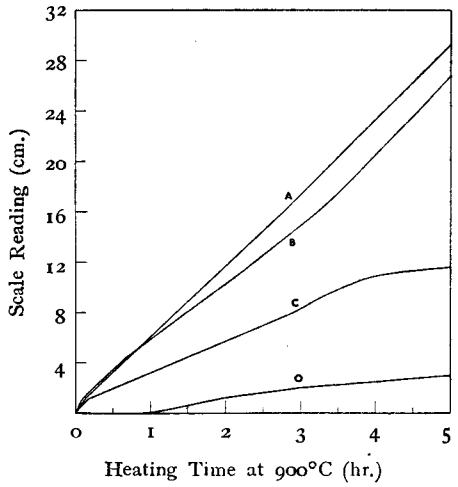
perature above Ac_1 point grow considerably. It is interesting to find the fact that the specimen pre-heated up to about 900°C grows more than other specimens.

In order to confirm the above phenomena, Specimen E was also treated in the same manner as Specimen B pre-heated in vacuo. Similar results were obtained as Fig. 6 shows.

Influence of pre-heating in various atmospheres. —Specimen C was pre-heated up to 900°C in vacuo, carbon monoxide and hydrogen. Then the growth of thus pre-heated specimens was measured in the air dilatometer at 900°C. According to the previous investigation, the expansion of grey cast iron at Ar transformation on the first cooling is largest in vacuo, very large in carbon monoxide but not so large in carbon monoxide as in vacuo, and far smaller in hydrogen than in any other atmosphere. The influence of these phenomena upon the growth was intended to be studied.

The results are shown in Fig. 8.

Fig. 8. (Specimen C.)



A: Specimen pre-heated in vacuo.
B: ,, CO.
C: ,, H_2.
O: Specimen in as cast state.

The growth in air at 900°C is larger, as the expansion at Ar transformation on the first cooling is larger during pre-heating; i.e., Ar transformation previously occurred in grey cast iron was found to have an intimate relation to the growth.

Moreover, the growth of the specimen in as cast state is less than that of one pre-heated in hydrogen in which Ar transformation did not accompany abnormal expansion. Accordingly other factors besides Ar transformation should be also taken into consideration.

Influence of various other modes of pre-heating. —Specimen D was treated in the air dilatometer as follows:

a) Heated up to 900°C. → Kept there for 3 hours. → Cooled down to 750°C (above Ar_1 point). → Heated again up to 900°C, and kept there for 5 hours.

b) Heated up to 900°C. → Kept there for 3 hours. → Cooled down to 750°C (above Ar_1 point). → Heated again up to 900°C. → Cooled again down to 750°C (above Ar_1 point). → Heated again up to 900°C, and kept there for 5 hours.

c) Heated up to 900°C. → Kept there for 3 hours. → Cooled down to 670°C (below Ar_1 point). → Heated again up to 900°C, and kept there for 5 hours.

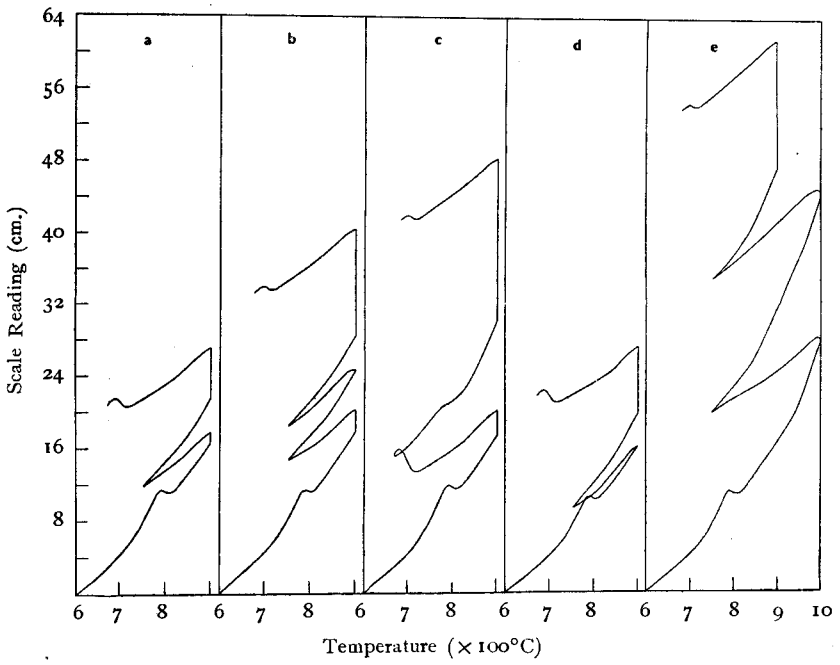
d) Heated up to 900°C. → Cooled down to 750°C (above Ar_1 point). → Heated again up to 900°C, and kept there for 5 hours.

e) Heated up to 1,000°C. → Cooled down to 750°C (above Ar_1 point). → Heated again up to 1,000°C. → Cooled again down to 750°C (above Ar_1 point). → Heated again up to 900°C, and kept there for 5 hours.

The results are shown in Fig. 9 (a-e).

Comparing Fig. a with Fig. d, the fact is observed that the final growth at 900°C in 5 hours is almost independent of the pre-heating time at 900°C when the latter time is at least 3 hours. In referring to Figs. a, b, d and e, we can also confirm that the specimen becomes susceptible to growth in air considerably when it is only repeatedly heated without passing through its Ar_1 point. It is also clearly shown from Figs. a and c that the specimen changes in its state to grow very easily when it expands abnormally at Ar transformation.

Fig. 9. (Specimen D.)

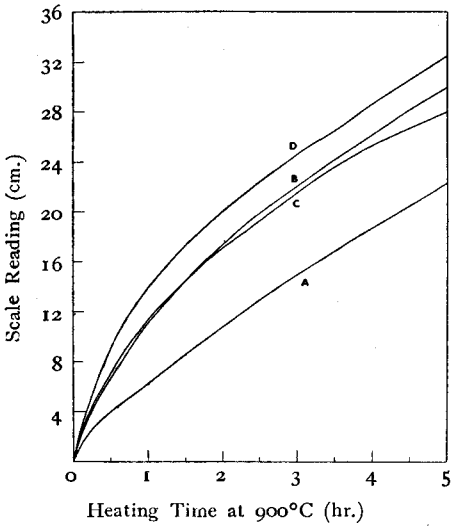


The experiments were next carried out on Specimen E and F as follows.

After they were previously heated repeatedly a predetermined number of times in vacuo and air at the temperature range between 850°C (above Ac_1 point) and 600°C (below Ar_1 point), their growth was measured in the air dilatometer at 900°C in the usual manner.

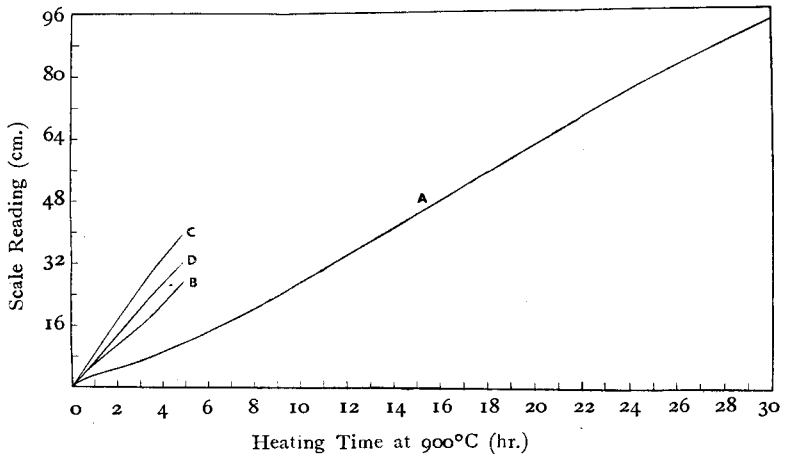
The results are shown in Fig. 10.

Fig. 10–1. (Specimen E.)



A: Specimen pre-heated in vacuo once.
B: „ 3 times.
C: „ 6 times.
D: „ 9 times.

Fig. 10–2. (Specimen F.)



A: Specimen pre-heated in air once.
B: „ 5 times.
C: „ 10 times.
D: „ 20 times.

The growth of the specimen pre-heated 3 times is far larger than that of one pre-heated once, but does not differ greatly from those pre-heated 5 to 20 times. As shown later, the abnormal expansion of grey cast iron at Ar transformation becomes smaller to disappear as the heating is repeated. If the abnormal expansion of grey cast iron at Ar transformation has an intimate relation to the growth, the present results may be understood from the above mentioned phenomenon.

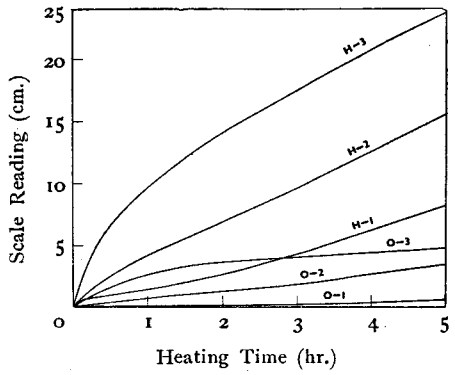
Influence of the heating temperature in air upon the growth of the specimen pre-heated in air.

Specimen G, pre-heated up to 900°C in air, was heated in the air dilatometer up to different temperatures—850°C, 930°C and 1,000°C for the measurement of the growth.

The results are given in Fig. 11, in which the growth of the specimen in as cast state is also shown.

The growth is larger as the heating temperature is higher.

Fig. 11. (Specimen G.)



O-1 : Specimen in as cast state ; at 850°C.
O-2 : „ 930°C.
O-3 : „ 1,000°C.
H-1 : Pre-heatd specimen ; at 850°C.
H-2 : „ 930°C.
H-3 : „ 1.000°C.

Influence of various atmospheres upon the growth of the specimen pre-heated in vacuo.

After Specimen H was pre-heated up to 900°C in vacuo, its growth in various atmospheres at 900°C was measured in 3 kinds of dilatometer.

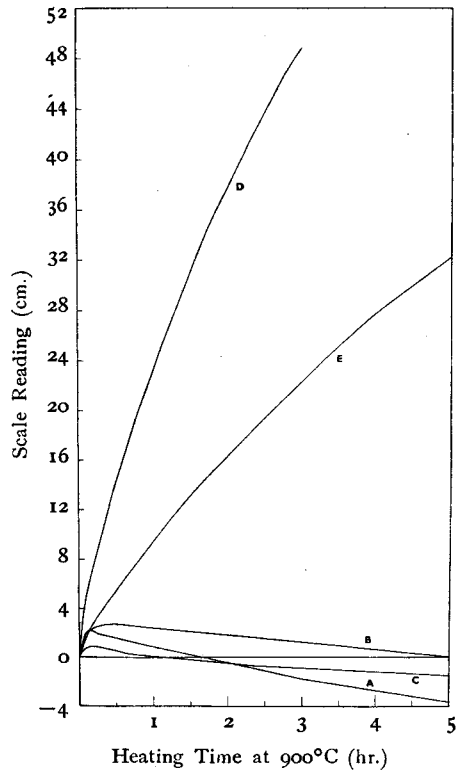
The method of introduction and the rate of flow of gases in the gas dilatometer were the same as in the previous investigation.

The results are shown in Fig. 12.

The pre-heated specimen rather contracts in vacuo, hydrogen and nitrogen. In air a considerable growth is shown. The fact that grey cast iron grows due to its oxidation is clearly proved from the present results.

The growth in carbon monoxide is shown to be larger than in air. The reason will be explained later.

Fig. 12. (Specimen H.)

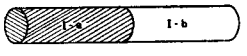


A : In vacuo.
B : „ H_2.
C : „ N_2.
D : „ CO.
E : „ air.

As before mentioned, the growth in air of grey cast iron pre-heated at high temperature is larger than one in as cast state, as the iron becomes susceptible to oxidation due to pre-heating. In order to confirm this conception further, the following experiments were carried out.

Two round bars I and II, 8 m.m. in diameter and 80 m.m. in length, were taken from Specimen F. They were divided into 2 pieces, then machined each to the size, 7.5 m.m. in diameter and 35 m.m. in length to be adopted as the specimen for the thermo-balance experiment. One of them (a in Fig. 13) was previously heated up to 900°C in vacuo and the other (b in Fig. 13) was used in as cast state. They were each heated up to 900°C and the change in weight at that temperature in still air was measured with Honda's thermo-balance.

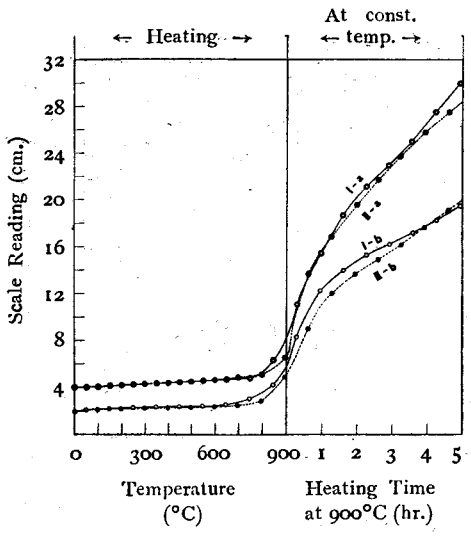
Fig. 13.



The results are shown in Fig. 14.

The weight increase after heating for 5 hours

Fig. 14. (Specimen F.)



I-a, II-a: Pre-heated specimen.
I-b, II-b: Specimen in as cast state.

Table II.

Weight increase due to oxidation at thermo-balance experiment.

Specimen No.	Weight before heating. (g.)	Weight after heating. (g.)	Weight increase due to oxidation. (%)
I-a (Pre-heated)	8.7338	8.9610	2.60
II-a(„)	8.0715	8.2852	2.65
I-b (In as cast state)	8.0285	8.1786	1.87
II-b(„)	8.0087	8.1597	1.89

at 900°C, expressed by a per cent. for the weight of the original specimen, is given in Table II.

As the specimen is decarburised at high temperature, the total quantity of oxygen taken by the specimen cannot be found from Fig. 14. We can, however, estimate the relative degree of oxidation of the specimen from the results obtained, because the specimen should be decarburised in increasing degree as its oxidation proceeds; that is, it may be understood that the greater weight increase of the specimen is due to the greater degree of its oxidation. Accordingly, Fig. 14 shows that the pre-heated specimen a was oxidised in greater degree than the specimen b in as cast state.

The growth of grey cast iron in carbon monoxide.

As before shown, a specimen of grey cast iron, pre-heated up to 900°C, grew considerably in carbon monoxide. The reason may be considered as follows.

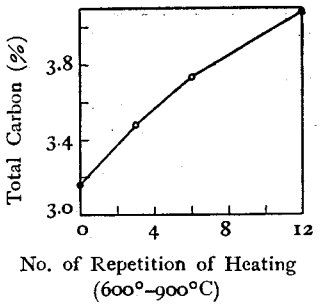
When carbon monoxide intrudes into the interior of grey cast iron which became sensitive for gas penetration due to pre-heating, it will decompose to carbon and carbon dioxide. The continuous deposition of carbon in fissures and cavities produces stresses which will cause the formation of cracks in the metal resulting in the permanent growth of the metal. It is just the same as the growth of iron ore which occurs when it is heated in carbon monoxide.

In order to confirm this consideration, the following experiments were carried out.

A flat bar, taken from Specimen G, was divided into 3 pieces, each having the dimension, 14 m.m. × 21 m.m. × 20 m.m. They were repeatedly heated in a porcelain tube at the temperature range between 600°C and 900°C in a current of carbon monoxide. The flow of the gas was 1 L./hr. in its rate and its direction was reversed every 20 minutes. After the required number of repetitions of heating was applied to the specimen, the latter was furnace cooled to be analysed for total carbon. In sampling for analysis, the thin layer of the surface of the specimen was discarded and the surface having the dimensions, 14 m.m. × 20 m.m., was scraped uniformly for sample.

The variation of the sample in its total carbon is shown in Fig. 15.

Fig. 15. (Specimen G.)



The total carbon increases almost linearly as the heating of the specimen is repeated. It is, of course, due to the fact that carbon monoxide decomposes in the interior of the specimen.

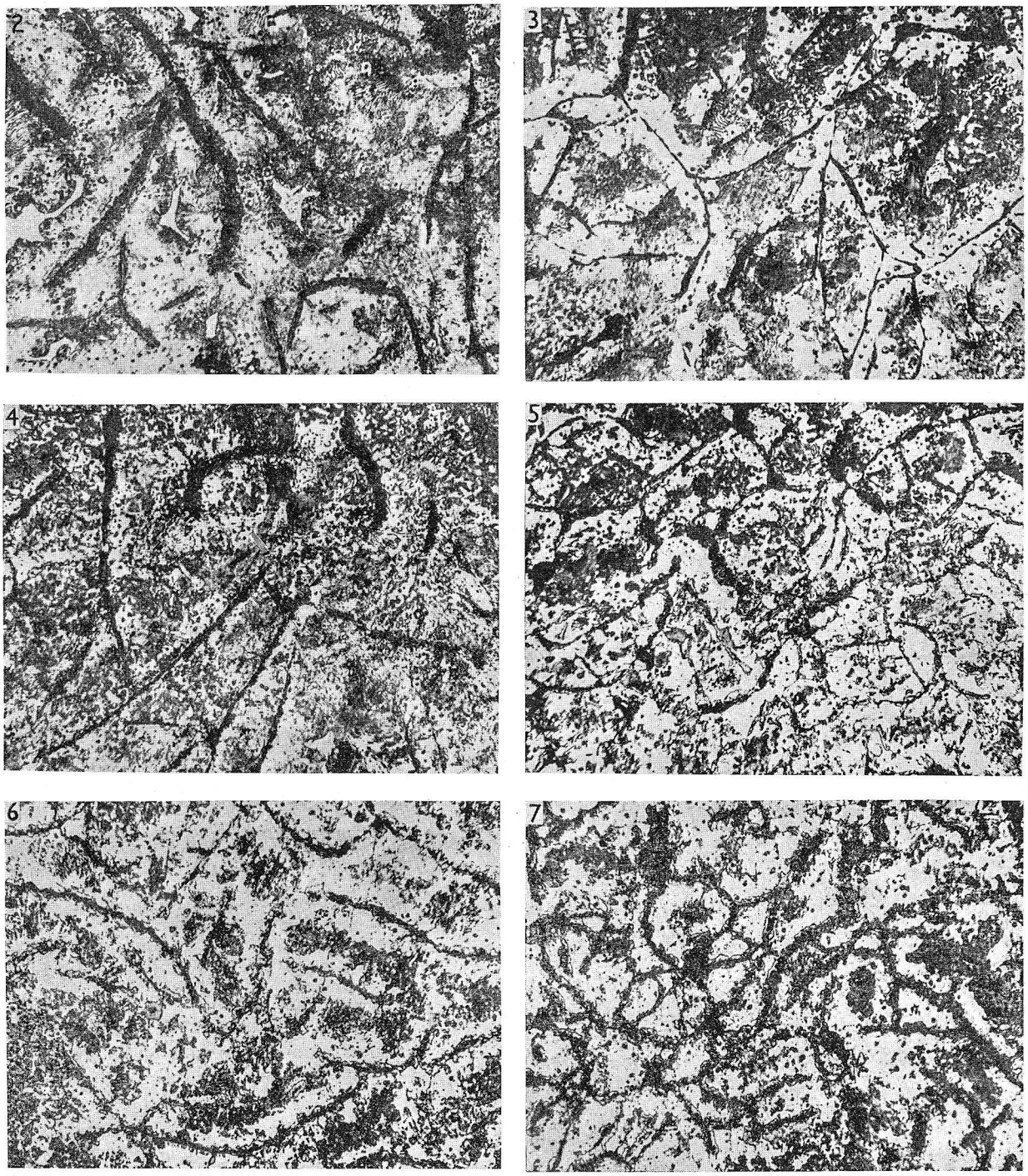
The microstructure of the surface of the middle part of the treated specimens is shown in Photos. 3 to 7.

As carbon monoxide is liable to intrude into the interior of grey cast iron through the space occupied by the graphites, carbon deposition will occur most vigorously around the graphites. Accordingly, the outline of the graphites becomes very indistinct due to carbon deposition as shown in Photos. 3 to 7. Carbon monoxide intrudes also into every fissure and crack, hence deposited carbon has the appearance similar to the graphites under the microscope as shown in Photo. 7 in the specimen to which a greater number of repetitions of heating was applied.

Further investigation on this problem is in progress in the author's laboratory as it is considered to be important in industry.

In the first report, the author gave a conclusion that the expansion of grey cast iron, occurring

Photos. 2–7 ×250



Specimen G.

2: As cast. 3: Heated 3 times in CO, outer part. 4: Heated 6 times in CO, inner part.
5: Heated 6 times in CO, outer part. 6: Heated 12 times in CO, inner part. 7: Heated 12 times in CO, outer part.

during cooling from the highest heating temperature to Ar_1 point, is not due to the internal oxidation, as it occurred even when grey cast iron was heated in the reducing atmosphere of carbon monoxide. But the author cannot help withdrawing his above words owing to the fact found in the present investigation.

When fissures and cracks in grey cast iron are filled with deposited carbon, the latter substance as well as oxidation products of the iron such as iron oxides, silica or silicates should act as an obstacle to the free contraction of the metal during cooling.

Comparison of the growth due to the abnormal expansion at Ar transformation with that due to oxidation.

One specimen of No. F was repeatedly heated 19 times in vacuo at the temperature range between 685°C and 850°C. The another specimen of the same number was also repeatedly heated 20 times in air at the temperature range between 650°C and 815°C. The growth-curves are given respectively in Fig. 16–a and Fig. 16–b. The relation between the number of cycle of heating and the growth or the expansion at Ar transformation indicated on the scale after every cycle of heating is obtained from Fig. 16 as shown in Fig. 17. The growth due to the graphitization of the pearlite-cementite on the first heating is discounted in this case. The relation between the number of cycle of heating and the cumulative growth on the scale is also found as shown in Fig. 18.

Fig. 16. (Specimen F.)

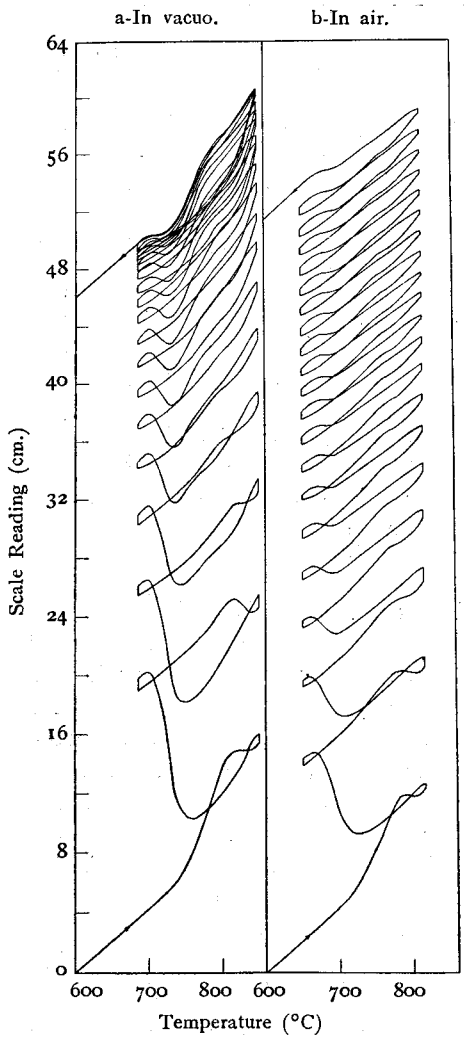
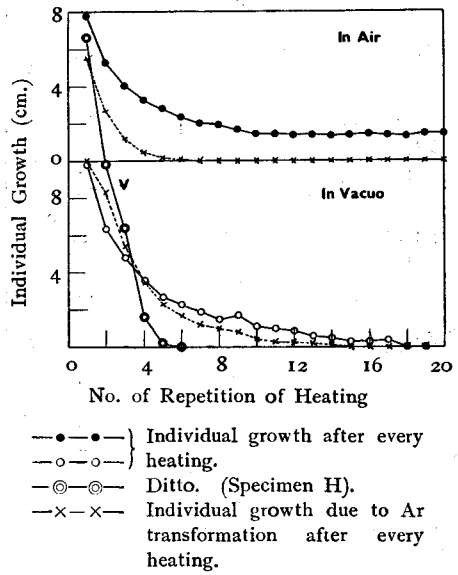
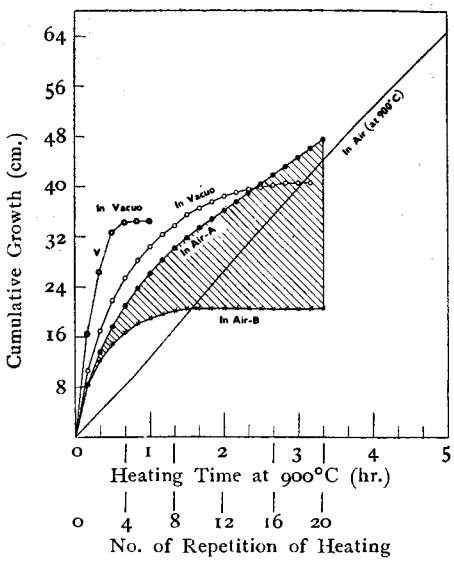


Fig. 17. (Specimen F.)



—●—●— } Individual growth after every
—○—○— } heating.
—◎—◎— Ditto. (Specimen H).
—×—×— Individual growth due to Ar transformation after every heating.

Fig. 18. (Specimen F.)



As clearly expressed in these curves, when the specimen is repeatedly heated in vacuo, the expansion at Ar transformation becomes smaller and smaller to disappear as the heating of the specimen is repeated. The change in the individual growth due to transformation is just the same as above, and the cumulative growth comes to a stop at the 18th heating. Accordingly, the greater part of the total growth in this case can be considered to be due to the expansion at Ar transformation. The same fact was already described in the first report. It is shown again in Figs. 17 and 18 (curve V, Specimen H).

The results of experiments in air greatly differ from the above case. The expansion at Ar transformation almost disappears at the 7th cooling. The cumulative growth, however, increased almost linearly as the heating of the specimen is repeated over 10 cycles. It is evident that the growth after the 10th heating is due to the oxidation of the specimen. Its magnitude is about 14 m.m. on the scale after every heating. Now, assuming that the growth of 14 m.m. on the scale occurs after every heating until the specimen is heated 10 times, the growth only due to transformation is expressed with the curve B in Fig. 18 in which the shaded part between the curves A and B will correspond to the growth due to oxidation. Accordingly, it may be approximately estimated that the growth due to the transformation is about 210 m.m. on the scale.

The specimen, heated 20 times in air in the above experiment, was heated again at 900°C for 5 hours in the air dilatometer in order to measure the growth at that temperature. The specimen grew further considerably as shown in Fig. 18;

Fig. 19–1. (Specimen F.)

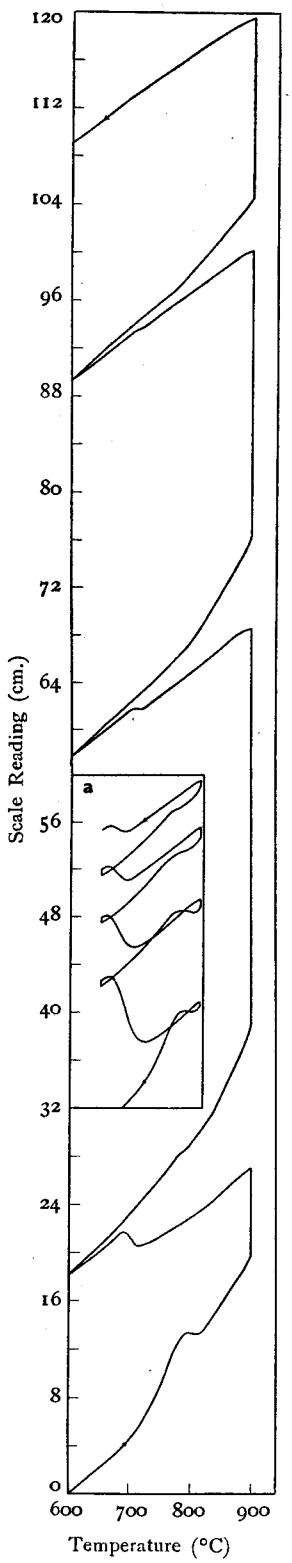
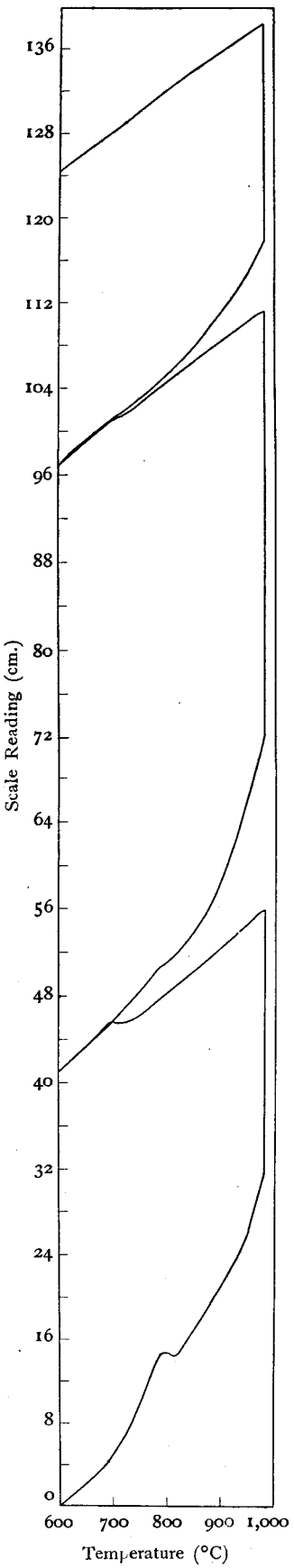


Fig. 19–2. (Specimen F.)

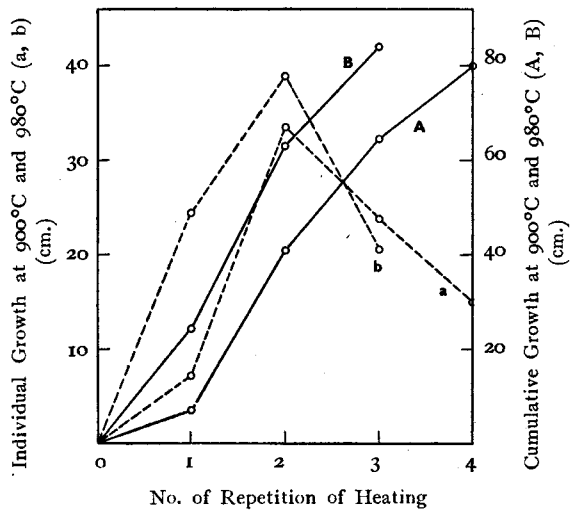


its growth is about 640 m.m. on the scale.

The other kind of cycle of heating was next applied to the other specimen of No. F in the air dilatometer, one cycle being as follows: Heated up to 900°C or 980°C.—Kept there constant for 5 hours.—Cooled down to room temperature.

The results are shown in Fig. 19, where the results of measurement obtained below 600°C are omitted. Fig. 20 shows the relation between the individual or cumulative growth and the number of cycle. Fig. 19–1-a is a reproduction of Fig. 16-b which shows the results of repeated heating of the same kind of specimen at the temperature range between 650°C and 815°C in air.

Fig. 20. (Specimen F.)



A, a: At 900°C.
B, b: At 980°C.

As clearly expressed in these figures, the expansion at Ar transformation occurs in far smaller magnitude in this case than in the case where the specimen is repeatedly heated without delay at the highest heating temperature. Moreover, it becomes smaller as the heating is repeated; when the specimen is heated at 980°C it becomes almost negligible on the second cooling. It is smaller when heated at 980°C than when heated at 900°C. That is, the greater is the degree of oxidation, the smaller is the expansion at Ar transformation.

When grey cast iron is exceedingly oxidized, the graphites are enveloped by oxidation products and the area of contact surface between the graphites and the metal is reduced. Hence, the graphites diffuse into the metal with difficulty in this condition. On the other hand, the decarburization of the austenite occurs more effectively as the metal is oxidized. Accordingly, the carbon content of the austenite becomes smaller as the metal is oxidized at high temperature resulting in the small magnitude of the abnormal expansion at Ar transformation which occurs due to the graphitization of the pearlite-cementite.

Further experiments were carried out on Specimen D as follows. After it was pre-heated

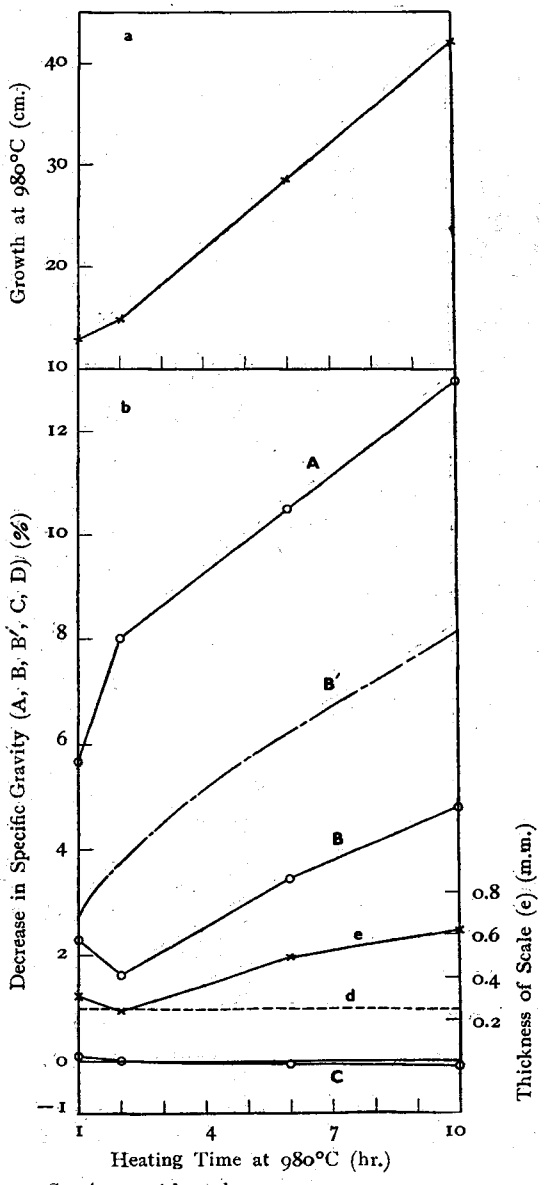
in air at 900°C, it was heated in the air dilatometer at 980°C for different durations of time in order to find the relation between the heating time at 980°C and the growth due to oxidation at that temperature or the growth due to the transformation of the pre-heated specimen.

The results are snmmarized in Fig. 21. Fig. 21-a shows the relation between the heating time and the growth at 980°C on the scale. The curve A in Fig. 21-b represents the decrease in specific gravity of the pre-heated specimens due to the treatment at 980°C. It was calculated after the specific gravity of the treated specimens covered with scale was measured. The specific gravity of the treated specimens was also measured after the scale was removed by hammering and grinding, and the per cent. of the difference in the specific gravity of the pre-heated specimens and the treated specimens without scale for the specific gravity of the pre-heated specimens was found as shown in the curve B. Photo. 8 shows an example of the structure of the treated specimens without scale; a to d show the continuation in structure from the outer to middle part. The change in specific gravity due to transformation was culculated from the magnitude of the contraction and expansion respectively at Ac and Ar transformation found during the growth-experiment of the pre-heated specimens and its per cent. for the specific gravity of the pre-heated specimens was determined as shown in the curve C. The decrease in specific gravity due to the transformation occuring during pre-heating was also calculated and its per cent. for the specific gravity of the specimen in as cast state was found as shown in the curve d. The curve e approximately shows the thickness of the scale produced on the surface of the specimens during growth-experiment.

It is clearly shown in this figure that the growth due to oxidation is far greater than that due to transformation and the latter is negligible in comparison with the former in the conditions of the present experiment. The growth due to oxidation will, of course, be greatest in the scale produced at the surface of the specimens and it becomes smaller in the inner part. The inner part surrounded by the scale, however, also grows pretty much as shown in the curve B. As a part of the metal was undoubtedly taken off together with the scale when the scale was removed from the specimen by grinding, the growth due to oxidation of the true metal core should be greater than that expressed by the curve B as qualitatively shown in the curve B′.

According to the results of the various experiments above mentioned, a general conclusion may be obtained that the growth due to transformation is far smaller than that due to oxidation and the greater part of the final growth should be due to oxidation when grey cast iron having common composition is repeatedly heated at high temperatures in oxidizing atmosphere.

Fig. 21. (Specimen D.)



A: Specimen with scale.
B: Specimen without scale.
B′: Ditto.—Imaginary curve.
C: Decrease due to transformation.
d: Decrease due to transformation after pre-heating.
e: Thickness of scale.

The theory on the growth.

The current theory on the growth was already briefly described in introduction of the present report. Besides the investigators before mentioned Outerbridge[9] believed that the growth occurs due

9) Trans. Am. Inst. Min. Met. Eng., 35 (1904) 223

Photo. 8.

×250

Specimen D.

Heated at 980°C in air for 6 hours.

to expansion of gases contained in grey cast iron. His theory was supported afterwards by Okochi and Sato[10] and Pearson.[11] The results of the present experiments, however, cannot be explained by this theory without any difficulty, and prove, on the other hand, that the oxidation theory is reliable. The abnormal expansion at Ar transformation has also an intimate relation to the growth as confirmed in the present experiments. It may be one of the primary causes for the growth. But the principal part of the growth was found to be due to oxidation of the metal itself. Consequently, the author agrees with the consideration of Benedicks and Löfquist or Piwowarsky who modified the Rugan and Carpenter's oxidation theory with the Kikuta's theory based on the abnormal expansion at Ar transformation.

When grey cast iron is heated in oxidizing atmosphere at high temperature, the oxidizing gases intrude into the interior of the iron along the spaces occupied by the graphites and other fissures and cavities and the iron is oxidized externally and internally at the same time resulting in the formation of the oxidation products such as iron oxides and iron silicates even in the metal part in contact with the graphites as shown by Scheil.[12] After Baeyertz[13], when a plain carbon steel containing 0.16 to 0.23 per cent. of silicon is heated at above 1095°C, iron silicates and iron oxides are formed at the grain boundary of the metal. The same phenomenon should be also observed in grey cast iron. The grey cast iron expands permanently due not only to formation of these oxidation products having larger specific volume than the metal, but also to internal bursting occurring in the metal with the key action of the oxidation products. Internal bursting may also occur even when the metal is simply heated and cooled without any accompanying discontinuous change in the volume of the metal, especially when the iron is heated or cooled through its critical range. Further oxidation of the metal should be promoted by the formation of the internal burstings.

Summary.

The results of the present investigation may be summarized as follows:

(1) When grey cast iron in as cast state is heated at high constant temperature in air, it grows but not so remarkably. When grey cast iron is treated in the same manner after being previously heated up to the temperature above its critical range, it grows remarkably and its growth is far greater than when grey cast iron in as cast state is heated in the same condition. Thus, it was confirmed that the abnormal expansion at Ar transformation of grey cast iron has an intimate relation to its growth.

(2) The growth of grey cast iron was measured in various gases and it was confirmed that it occurs due to its oxidation.

(3) When grey cast iron is heated at high temperature in oxidizing atmosphere, it grows principally due to its oxidation. The abnormal expansion at Ar transformation may be one of the primary causes for the growth in some case but far less important in comparison with oxidation.

(4) A considerable growth of grey cast iron was found in carbon monoxide. It is due to deposition of carbon by dissociation of this gas in the internal fissures and cavities and the spaces occupied by the graphites.

In conclusion, the author desires to express his cordial thanks to Toyoda Jidoshokki Seisakusho, Kariya near Nagoya, for financial support and also to Mr. J. Yamamoto for his kind assistance.

10) J. Coll. Eng. Tokyo Imp. Univ., 10 (1920) 53
11) Carn. Scholarship Mem. (Jour. Ir. St. Inst.) (1926) 281
12) Arch. f. Eisenhüttenw., 6 (1932) 61
13) Trans. Am. Soc. Met., 24 (1936) 420