Nitrogen as Alloying Element in Steels. II : On the Effect of Nitrogen on Blue-Brittleness in Steels

著者	IMAI Yunoshin, ISHIZAKI Tetsuro
journal or publication title	Science reports of the Research Institutes, Tohoku University. Ser. A, Physics, chemistry and metallurgy
volume	4
page range	553-574
year	1952
URL	http://hdl.handle.net/10097/26538

Nitrogen as Alloying Element in Steels. II
On the Effect of Nitrogen on Blue-Brittleness in Steels*

Yûnoshin IMAI and Tetsuro ISHIZAKI

The Research Institute for Iron, Steel and Other Metals

(Received September 19, 1952)

Synopsis

To ascertain the effect of nitrogen on the blue-brittleness in carbon steels, usual tensile tests were carried out at temperatures above room temperature up to 300°, and it was found that nitrogen was the principal cause of this phenomenon, although the brittleness due to carbon was seen at a high temperature range in steels containg low nitrogen.

I. Introduction

When iron or steels are heated up to temperatures between 150 and 3C0°, they become somewhat brittle, that is, their hardness and tensile strength become higher than those at room temperature, while their impact values gradually decrease as the testing temperature is raised above 100°, showing minimum values at about 400~5C0° according to their compositions. These phenomena were called the blue-brittleness in steels and have been studied by many investigators. The important results will briefly be mentioned below.

Fettweis(1) identified age-hardening as blue-brittleness in iron and steels, and Ludwik(2) considered age-hardening in steel to be caused by precipitation. Dean, Pay and Gregg(3) reported that the brittleness had some correlation with nitrogen in steels, showing remarkable blue-brittleness due to the presence of nitrogen. Fettweis' hypothesis(1) was confirmed in a non-aging steel made by drastic deoxidation, in which oxygen, nitrogen and carbon were probably fixed so that they could not go in or out of solution to give the dispersion effect. Eilender, Cornelius and Menzen(4) examined the effects of nitrogen, oxygen, sulphur, phosphorous and manganese on the tensile properties at the blue-brittle temperature range, that is. at about 2C0°, and showed that there was a certain relation between the blue-brittleness and the nitrogen content in normalized steels, while oxygen, sulphur and phosphorous had almost no effect on them. Enzian(5) showed that the blue-brittleness in low carbon steels was made remarkable by nitrogen content, although phosphorous had no effect on it.

---

* The 693rd report of the Research Institute for Iron, Steel and Other Metals.

(1) F. Fettweis, Stahl u Eisen, **39** (1919), 34.
(2) P. Ludwik, Z. Ver. deutsch. Ing. **70** (1926), 379.
(3) R. S. Dean, R. O. Day and J. L. Gregg, A. I. M. E., **84** (1929), 446.
(4) W. Eilender und H. Cornelius, Arch Eisenhüttenwes., **14** (1940/41), 217.
(5) G. H. Enzian, J. Met., Vol. (1950), 346.

In our first report, the study on the effect of nitrogen on temper-brittleness was mentioned, in which nitride precipitated along the solubility curve was shown to play an important role in the temperbrittleness in a steel. In the present case, an investigation was carried out to ascertain the effects of nitrogen, carbon and manganese on blue-brittleness, and of aluminium or titanium for denitrogenizer.

Part A

The effect of nitrogen on the blue-brittleness was first studied with low carbon steels and low manganese steels containing various percentage of nitrogen by tensile test.

II. Preparation of specimen and method of experiment

Blue-brittleness may be examined either on mechanical or on physical properties of a steel. It is, however, statical mechanical properties that the phenomenon manifests itself most conspicuously. Therefore, a tensile test was carried out. The materials used in preparing specimens were electrolytic iron containing the lowest phosphorous and sulphur, white cast iron made specially from the above electrolytic iron and gas carbon, and electrolytic manganese. They were melted in high frequency electric furnace.

In order to change the nitrogen content in each specimen, the melting was carefully carried out, that is, an adequate amount of $CaCN_2$ was used for the specimens in which manganese should not be contained, whereas, for the specimens in which manganese should be contained nitrogenized manganese and $CaCN_2$ were used. The remainder of nitrogen depended on the melting conditions of the specimen, which will be reported in detail in the subsequent papers.

After forging by about 14 mm in diameter, the specimen was heated at 950° for 15 minutes and air-cooled, from which tensile test-pieces, 35 mm in parallel part, 25 mm in gauge length and 6 mm in diameter, were machined. In order to get rid of any working strain and unstable structure, the specimens were heated at 550° for 3 hours and then slowly cooled in vacuum at the rate of about 25 per hour. The diminishing of blue-brittleness after vacuum heating will be reported in detail in the subsequent paper, but as the above-mentioned treatment gave almost no effect on the blue-brittleness, all the specimens were annealed in this way.

The tensile test was made at the rate of 5 mm/3 min, which was held as constant as possible. The testing temperature ranged from room temperature to 350°. The specimen was first heated at the temperature 10° above it and then cooled at the rate of about 1°C/min; it was further held at the testing temperature for 10 minutes and then put to the test. In heating the specimen, brass plate, 0.5 mm in thickness and five turns, was put inside an electric resistance furnace, and the uniformly heated state of the specimen was confirmed by the differential thermal junction, with the result that the temperature difference in the parallel part was less than ±1°.

III. Results of experiments

1. On the specimens of melted electrolytic iron

Electrolytic iron was first melted and then an adequate amount of $CaCN_2$ was added to it to vary its nitrogen content and finally it was deoxidized by Si. Table 1 shows the chemical analyses of these specimens. Figs. 1~6 show the change of tensile strength (σ_B), yield point (σ_s), elongation (δ) and reduction of area (ϕ) of the steels 1~6 with temperature.

Table 1. Result of Chemical Analysis for Pure Iron.

	Chemical Composition Percent			
	C	Si	Mn	N_2 *
No 1	0.022	0.046	trace	0.003
No 2	0.029	0.049	"	0.004
No 3	0.028	0.030	"	0.005
No 4	0.030	0.042	"	0.008
No 5	0.029	0.040	"	0.018
No 6	0.034	0.033	"	0.023

Analysis on the sample air cooled from 950°.

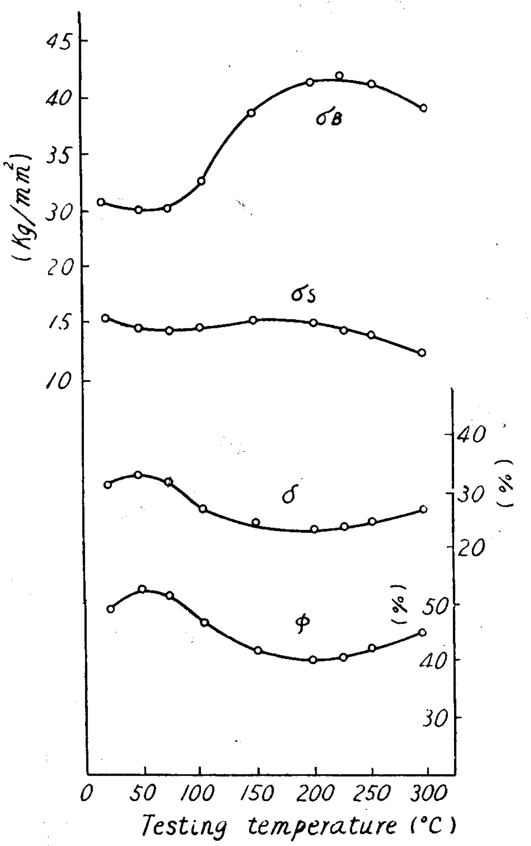

Fig. 1

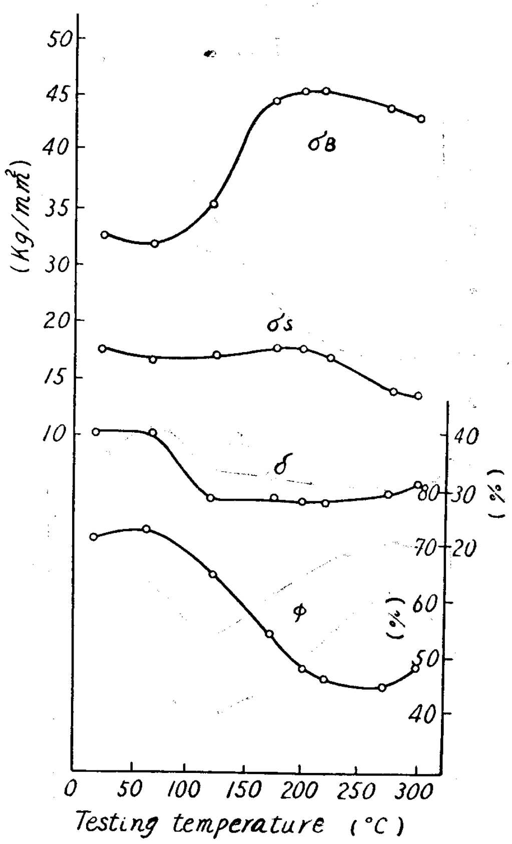

Fig. 2

As clearly seen in these figures, the tensile strength began to increase at about 70°, and the maximum value was situated between 180° and 260°, shifting

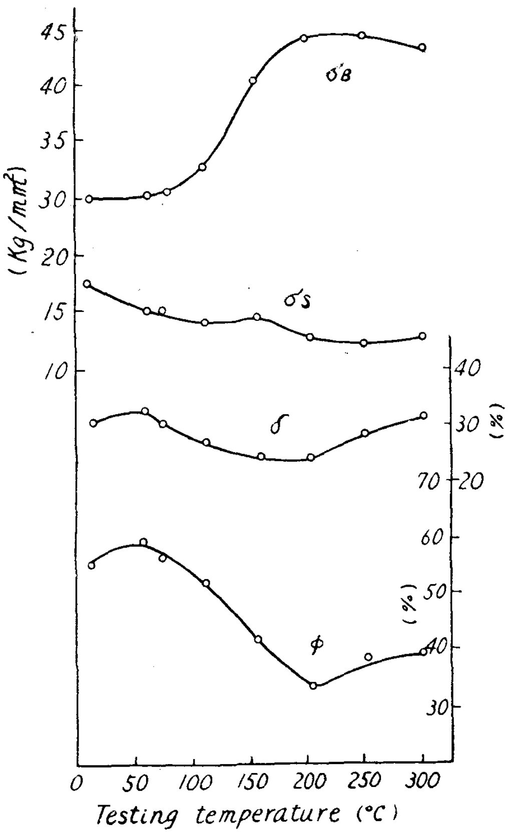

Fig. 3.

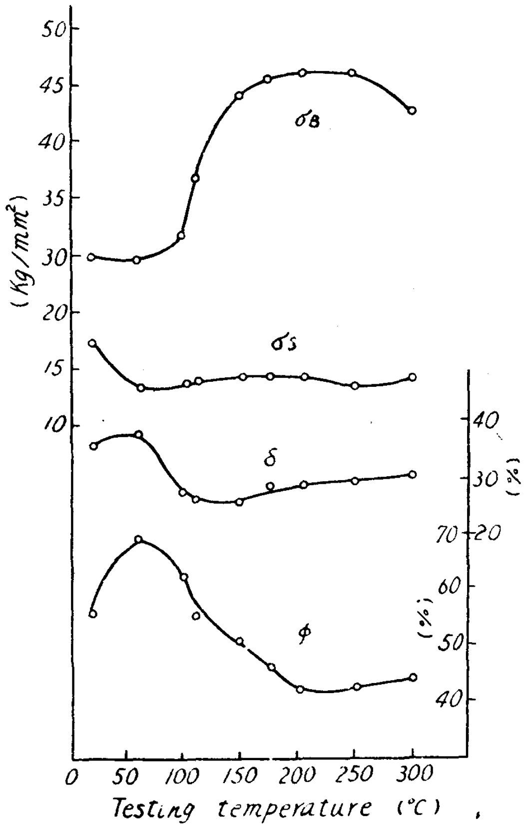

Fig. 4.

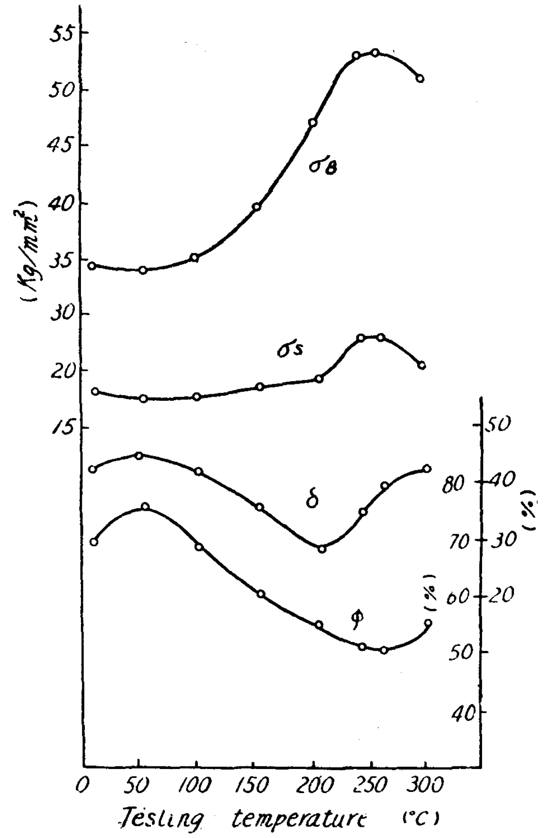

Fig. 5

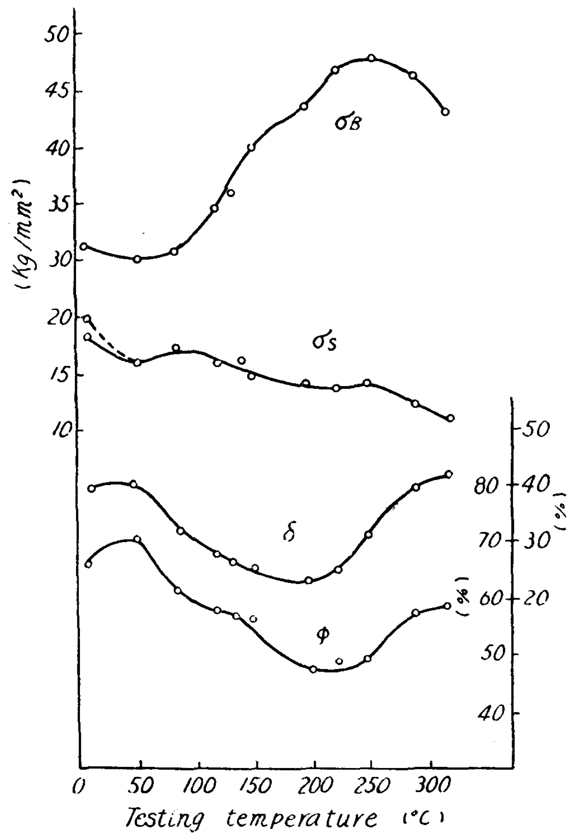

Fig. 6

towards high temperature side with the increase of nitrogen content. Further, the tensile strength curves of the steels containing low nitrogen are comparatively flat in the vicinity of the maximum point, while those of the steels containing high nitrogen are sharp. The reason for this phenomenon will be given in detail in the subsequent papers, but, briefly speaking, this would probably be caused by the existence of carbon in the steel. The blue-brittleness appeared at somewhat lower temperature in the δ-curve than in the σ_B-curve, the minimum value of the elongation being at lower temperature side than the maximum value of the tensile strength. As in the case of the σ_B-curve, the δ-curves of the steels with high content of nitrogen were sharp in the vicinity of the maximum value, going down rapidly at about 200°. The change of the reduction of area (ϕ) showed almost the same results as in the case of the tensile strength. As to the yield points (in the figures, the marks and are referred to the upper and the lower yield points, respectively), the blue-brittleness and the change thereafter were almost uniform, so it seemed probable that the blue-brittleness had only a small effect on the yield point, though the change of the yield points was seen somewhat clearly in the steels 7~11 which will be dealt with later.

Further, the ratio of the difference between the maximum and minimum tensile strength to the minimum tensile strength was taken as the rate of increase in the tensile strength, and the ratio of the decreasing amount, respectively, of the elongation and the reduction of area to their maximum values were taken as the rate of decrease in these two properties. The relations between the ratios above mentioned and the nitrogen content are shown in Fig. 7. As seen in this figure, the increasing

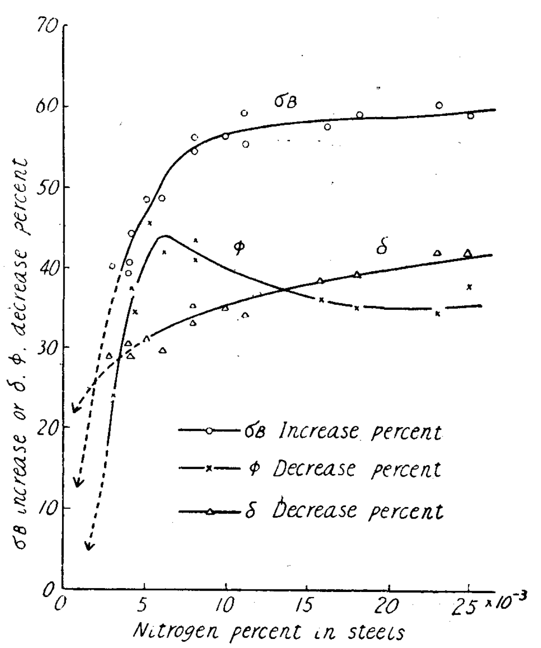

Fig. 7

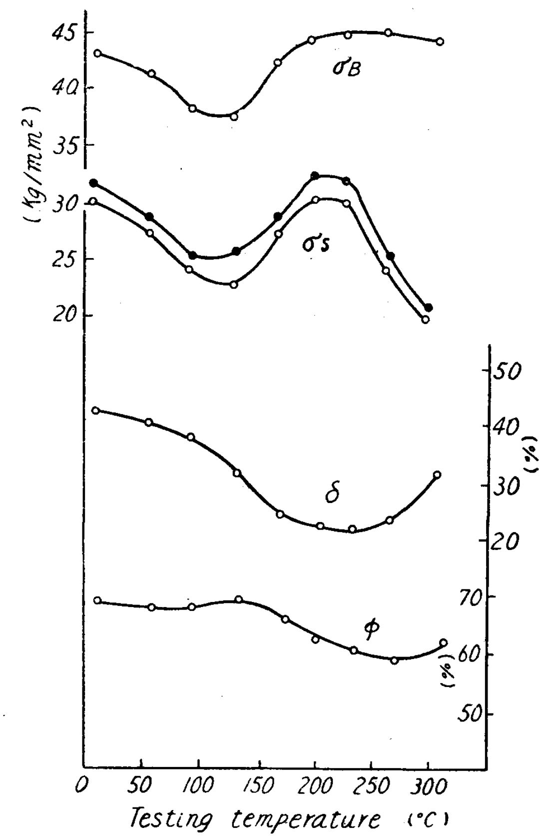

Fig. 8

of the tensile strength with the increase of the nitrogen content are remarkable up to 0.008 per cent of nitrogen and somewhat slowly in the case of more nitrogen content. The change of the elongation also decreased with the increase of the nitrogen content, showing a rapid decrease at the side of low content of nitrogen.

The change in the reduction of area rapidly decreased up to the nitrogen content of 0.006 per cent and then slowly. In this figure it will particularly be noticed that, as shown in the dotted lines, the rate of increase in the tensile strength and the rates of decrease in the elongation and reduction similarly tend to zero with the decrease of nitrogen content, showing almost no blue-brittleness at the point without nitrogen. This may be said that the blue-brittleness will be caused mainly by the existence of nitrogen in steels. As will be reported in detail in the subsequent papers, the above remark will be confirmed more clearly when steels are denitrogenized with aluminium and titanium or witn hydrogen. The reason why the curves of the rate of increase in tensile strength, the rates of decrease in elongation and reduction take such a form as shown in Fig. 7 will be discussed in the subsequent papers.

2. On steels with 0.1 per cent of carbon and 0.4 per cent of manganese

Table 2 shows the chemical analyses of the steels 7~11 and Figs. 8~12 are their experimental results. In the steel 7 containing low nitrogen (Fig. 8) the tensile strength began to increase at about 120°, but with the increase of nitrogen content this beginning point gradually moved towards low temperature side, while in the steels 10 (Fig. 11) and 11 (Fig. 12) the tensile strength began to increase at about 70°. In the case of the electrolytic iron mentioned above, the transition of the beginning point was not observed in this manner. This difference will probably be caused by the existence of manganese in the steels.

Table 2. Result of Chemical Analysis for low Carbon Steel.

	C	Si	Mn	N_2
No 7	0.17	0.21	0.43	0.003
No 8	0.11	0.18	0.38	0.007
No 9	0.11	0.19	0.42	0.010
No 10	0.14	0.17	0.36	0.013
No 11	0.12	0.23	0.34	0.020

The upper and lower yield points were equally clearly measured in the steels of this kind and both increased at the outset of the blue-brittleness and then decreased. Some investigators said that the blue-brittleness had not been observable in the yield points, but, according to the present experiment, it was observed, though not so conspicuous as in tensile strength, elongation and reduction of area. Further, as can clearly be seen in the figures, the changes of the tensile strength, elongation and reduction of area were entirely similar to those in the above-mentioned experiments.

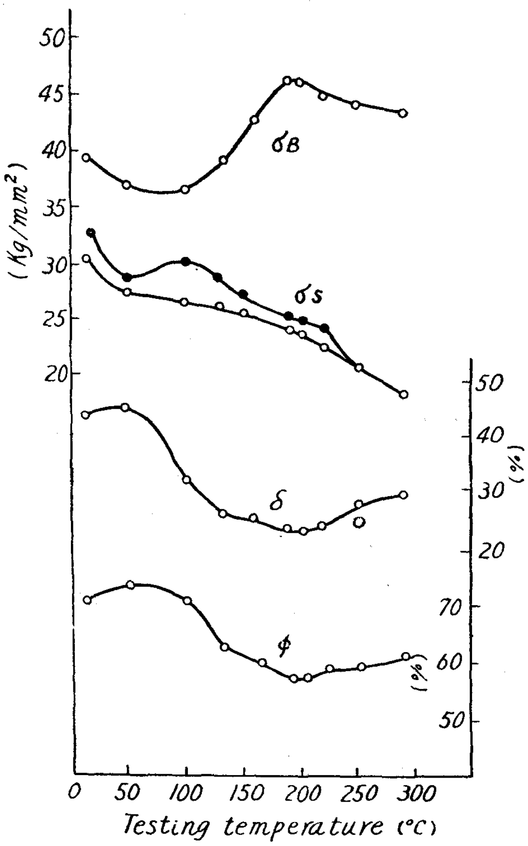

Fig. 9

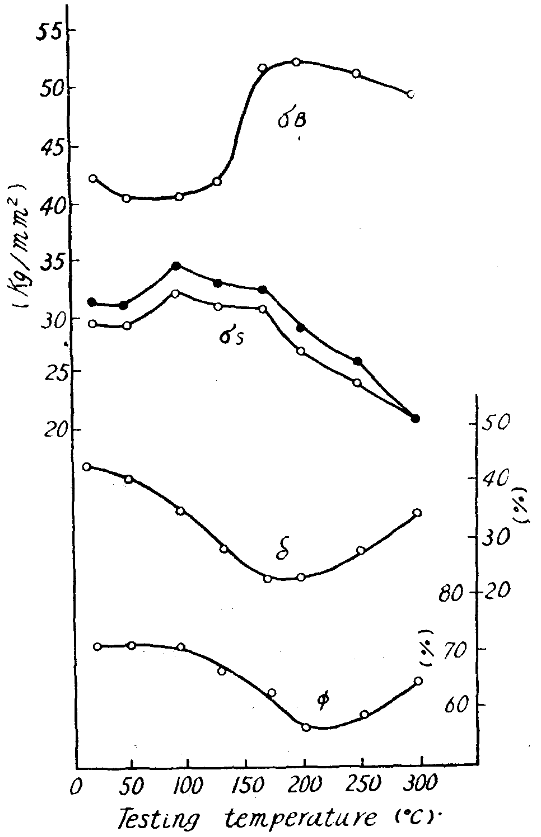

Fig. 10

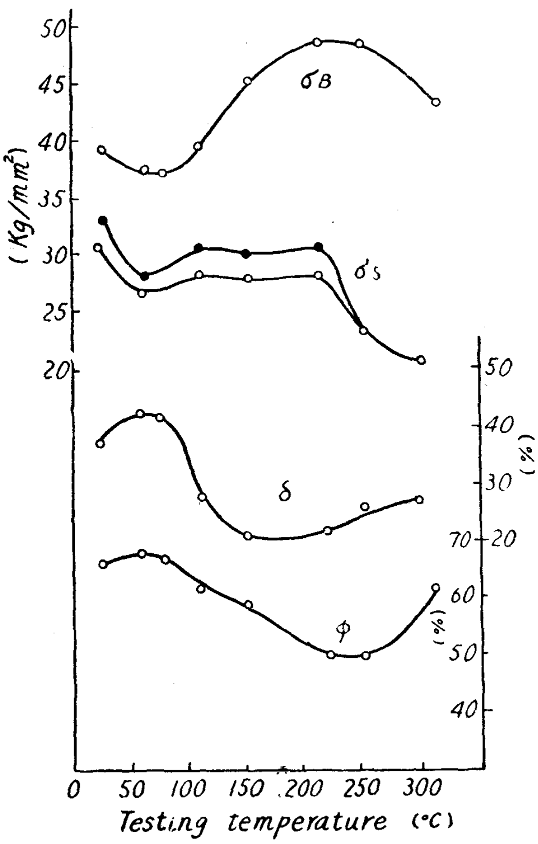

Fig. 11

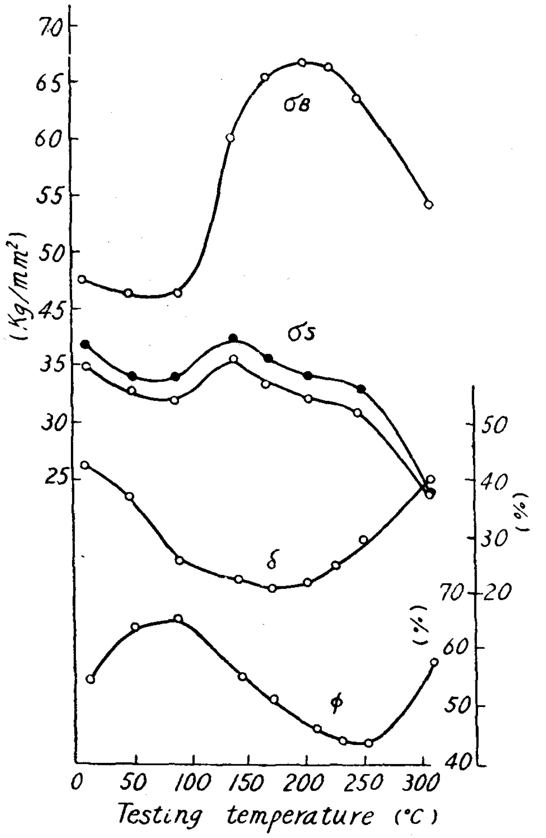

Fig. 12

Fig. 14 shows, as Fig. 7, the relations of the rate of increase in the tensile strength and of the rates of decrease in the elongation and reduction to the nitrogen content. They all increased with the amount of nitrogen, that is, the blue-brittleness became remarkable with the increase of the nitrogen content. As already shown in Fig. 7, if the blue-brittleness disappeared in the steel without nitrogen, it would vary as shown by the dotted line in Fig. 13. In this case, however, the bluebrittleness rapidly increased up to the nitrogen content of about 0.005 per cent, and then comparatively slowly with the increase of nitrogen content. That is, the point at which the blue-brittleness occurred is situated at lower nitrogen side than the case of the electrolytic iron shown in Fig. 7. This will probably be caused by the existence of carbon. The effect of manganese on the blue-brittleness will be shown later.

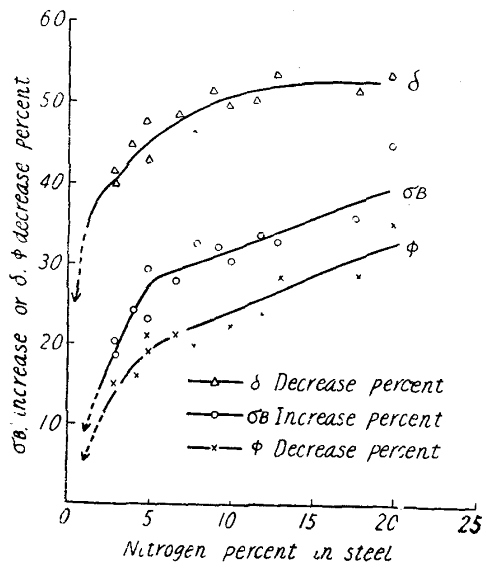

Fig. 13.

3. On the steels made from electrolytic iron by deoxidation with manganese and silicon

Samples were all prepared by melting electrolytic iron under the conditions, under which the melt could first absorb sufficient air and was then added nitrogen by using a small amount of nitrided manganese and $CaCN_2$ and was finally deoxidized with manganese and silicon by usual method. Thus, the nitrogen content in these steels was fairly high as compared with above two cases. Table 3 shows the chemical analyses of these steels and Figs. 14~21 are their experimental results.

Table 3. Result of Chemical Analysis for Iron containing Mn and Si.

	Chemical Composition Percent			
	C	Si	Mn	N_2
No 12	0.028	0.14	0.30	0.012
No 13	0.035	0.13	0.22	0.017
No 14	0.038	0.10	0.18	0.018
No 15	0.030	0.17	0.20	0.022
No 16	0.030	0.13	0.27	0.025
No 17	0.033	0.16	0.29	0.029
No 18	0.034	0.15	0.26	0.031
No 19	0.023	0.12	0.18	0.034

In the case of these steels, the tensile strength also began to increase at about 70° as in the above case, the maximum point also moving to high

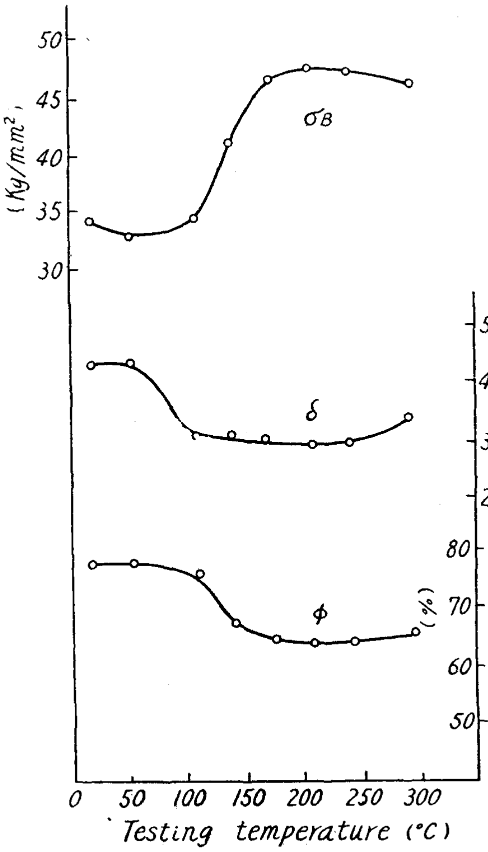

Fig. 14

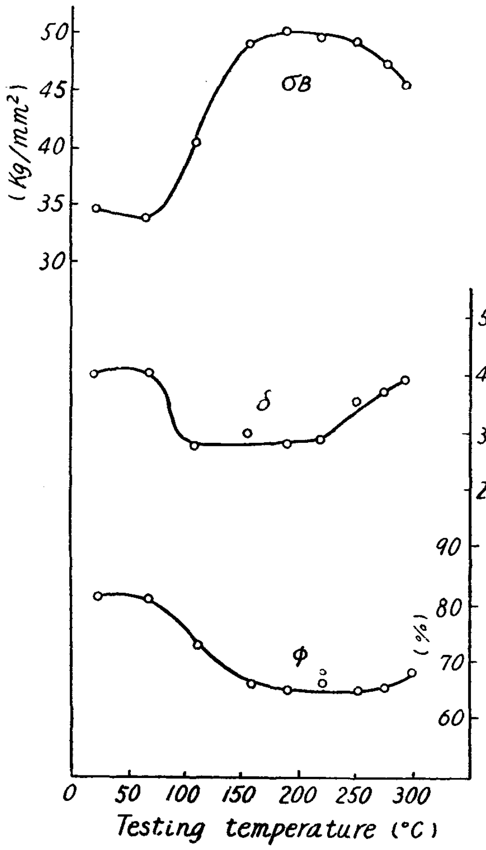

Fig. 15

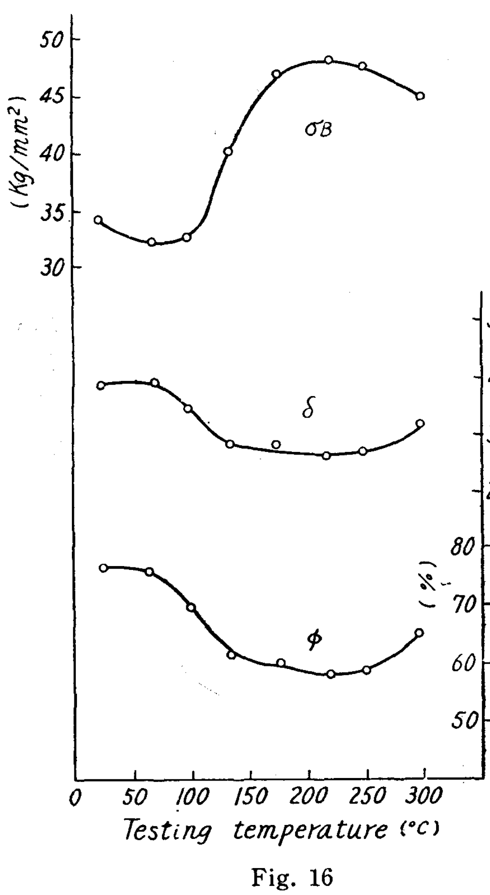

Fig. 16

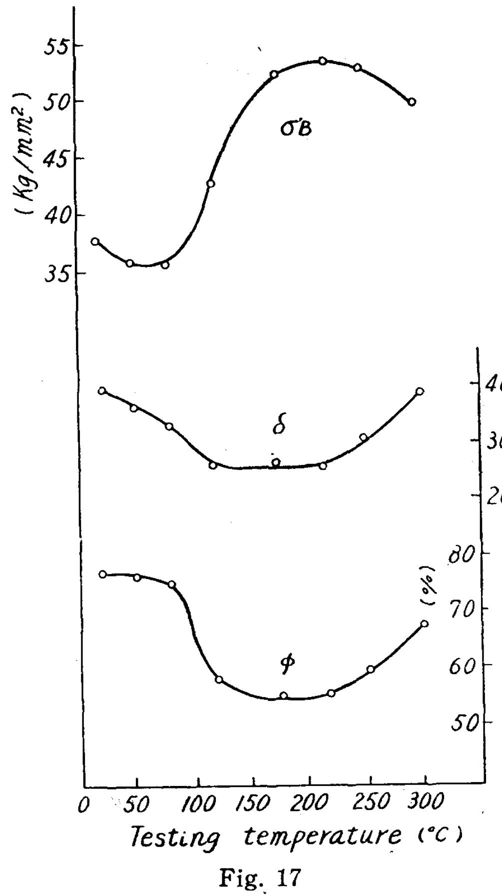

Fig. 17

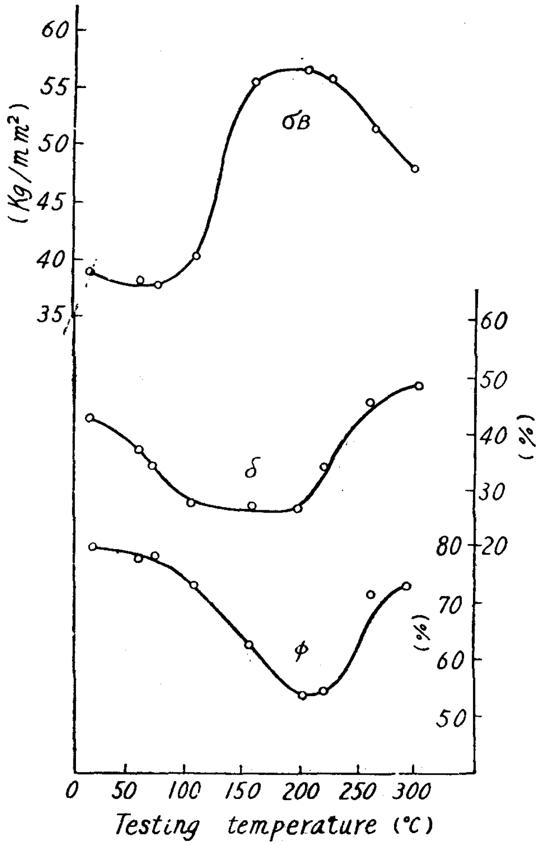

Fig. 18

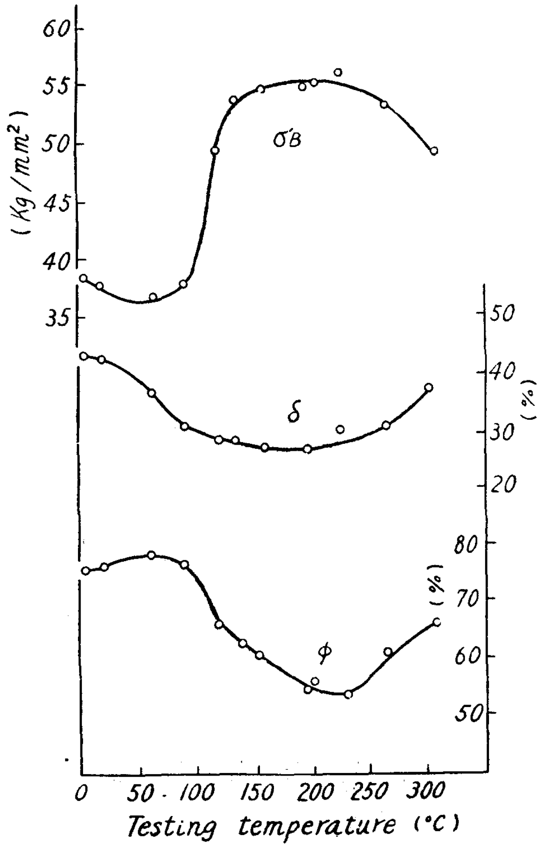

Fig. 19

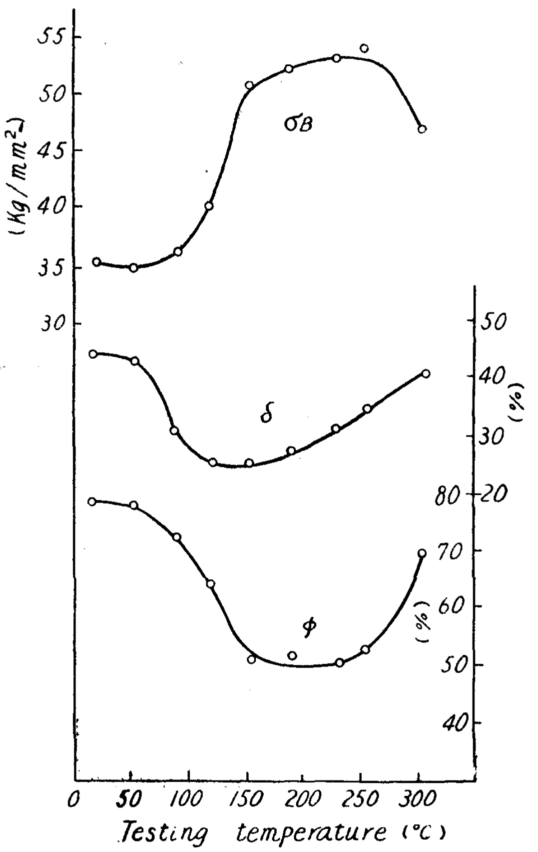

Fig. 20

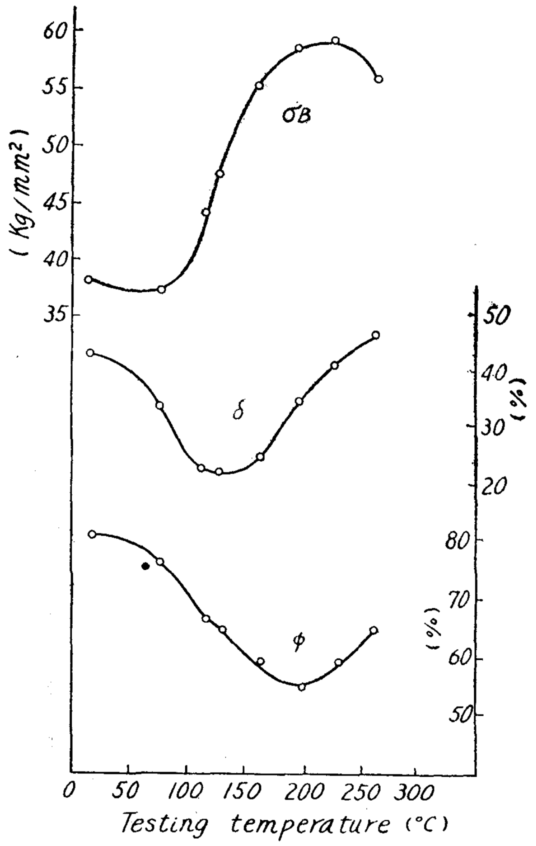

Fig. 21

temperature side with the increase of the nitrogen content. The changes of the elongation and reduction were the same as in the case of Sec. 1. In steels containing less nitrogen, the recovery of blue-brittleness due to heating was slowly, while, in the steels containing more nitrogen, the brittleness was rapidly recovered. Fig. 22 shows, as Figs. 7 and 13, the relations of the rate of increase in the tensile strength and of the rate of decrease in the elongation and reduction of area to the nitrogen content. From this figure, it can be seen that the blue-brittleness increases with the nitrogen content and that the degree of the blue-brittleness in these steels is small, compared with that in the steels shown in Table 1. This is due to the existence of manganese, which will be mentioned in detail in the next section treating the steels containing 1.2 per cent of manganese.

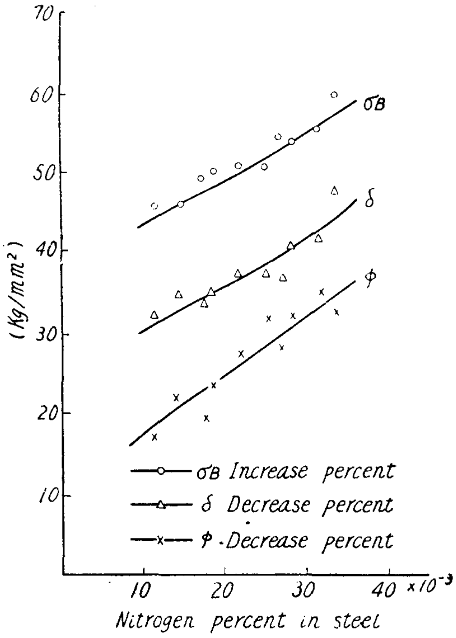

Fig. 22

4. On the low manganese steels containing 0.4 per cent of carbon and 1.2 per cent of manganese

Low manganese steels containing 0.4 per cent of carbon and 1.2 per cent of manganese were prepared by usual melting method, adding nitrogen to it by using nitrided manganese. Table 4 shows the chemical analyses of these steels.

Table 4. Result of Chemical Analysis for low Manganese Steel.

	Chemical Composition Percent			
	C	Si	Mn	N_2
No 20	0.34	0.33	1.36	0.016
No 21	0.42	0.29	1.35	0.017
No 22	0.34	0.33	1.04	0.025
No 23	0.34	0.24	1.03	0.033
No 24	0.38	0.28	0.45	0.018

Figs. 23~26 show the experimental results of the steels 20~23. In these steels, the tensile strength began to increase at about 150°, except the steel 23 (seen in Fig. 26), in which it began to increase at about 100°. From this fact it can clearly be seen that the beginning point of the blue-brittleness changes with the nitrogen content. Further, in the steels 20~22, the maximum value of the tensile strength was low, not reaching the value at room temperature. This will be due to the circumstances that the high content of manganese will check the nitride formation and that the increased amount of pearlite will remarkably reduce the brittleness.

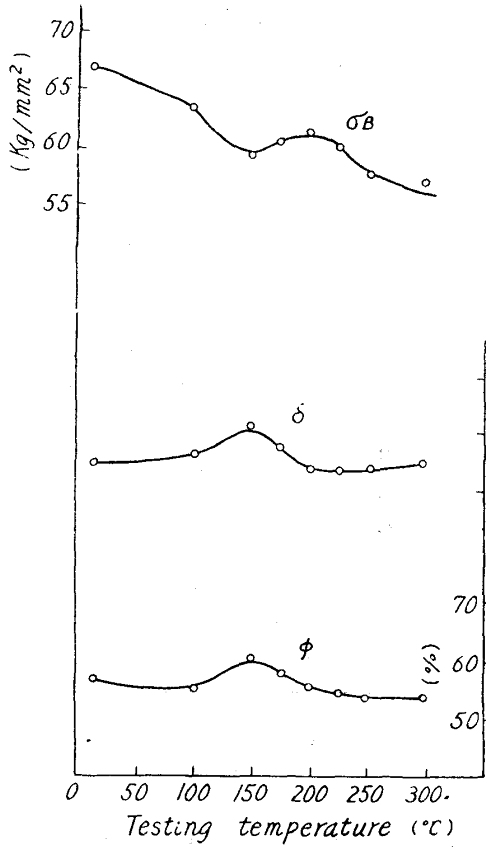

Fig. 23

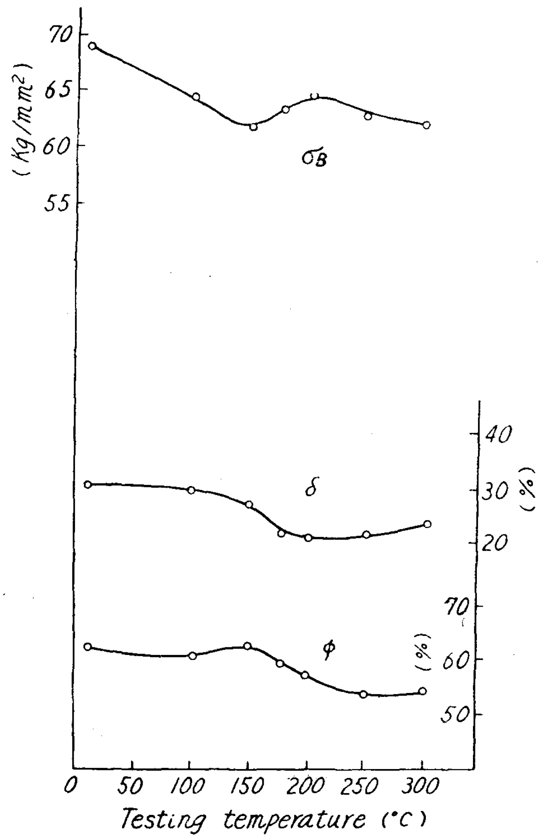

Fig. 24

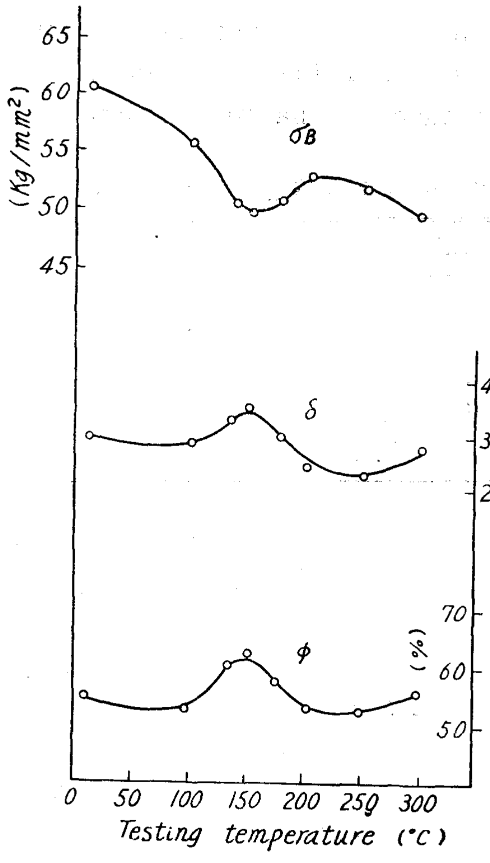

Fig. 25

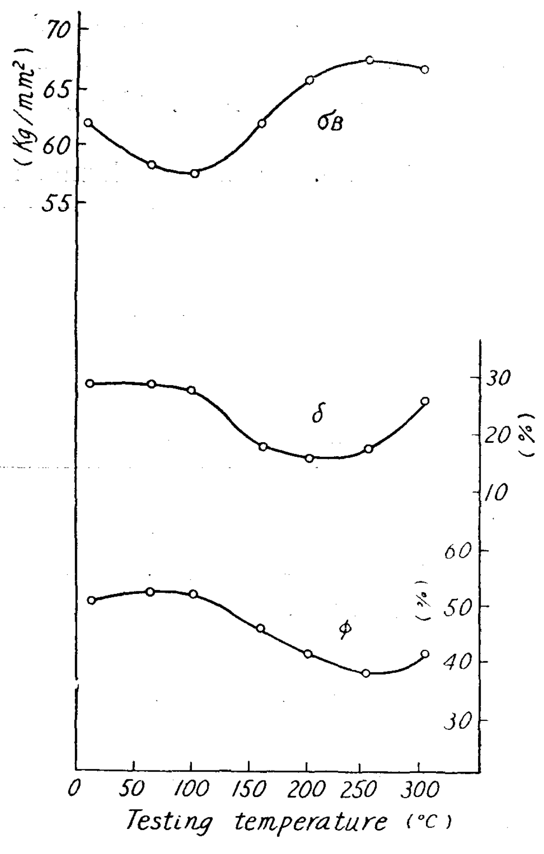

Fig. 26

Fig. 27 shows the relations of the rate of increase in the tensile strength and of the rates of decrease in the elongation and reduction of area to the nitrogen content. As clearly be seen in this figure, the blue-brittleness becomes remarkable with the increase of the nitrogen content and will almost disappear when the nitrogen content tends to zero.

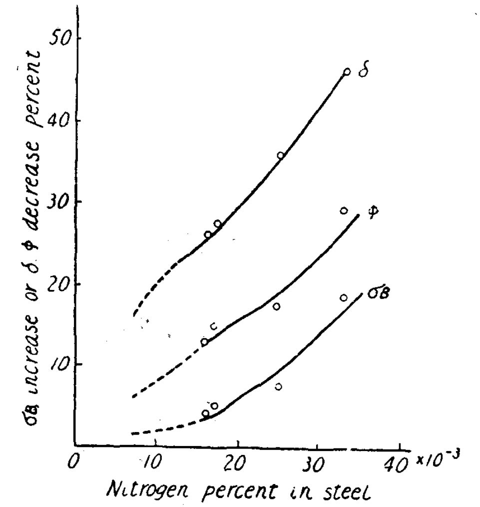

Fig. 27

In order to clarify the effect of manganese on the blue-brittleness, the steel 24 containing the same amount of nitrogen but a different amount of manganese was tested, the results of which is shown in Fig. 28. Comparing this with Fig. 24, it will easily be seen that the beginning point of the brittleness is at about 150° in the latter, where as in the former it is at about 80° and that in the former the maximum value of the tensile strength does not reach the value at room temperature, while in the latter it is clearly raised above this value. For the reason that manganese checks the occurrence of the blue-brittleness, steels containing high manganese will show only a slight brittleness at high temperatures provided the nitrogen content is the same. Accordingly, if the nitrogen content is increased without changing the amount of manganese, the brittleness will appear at lower temperatures.

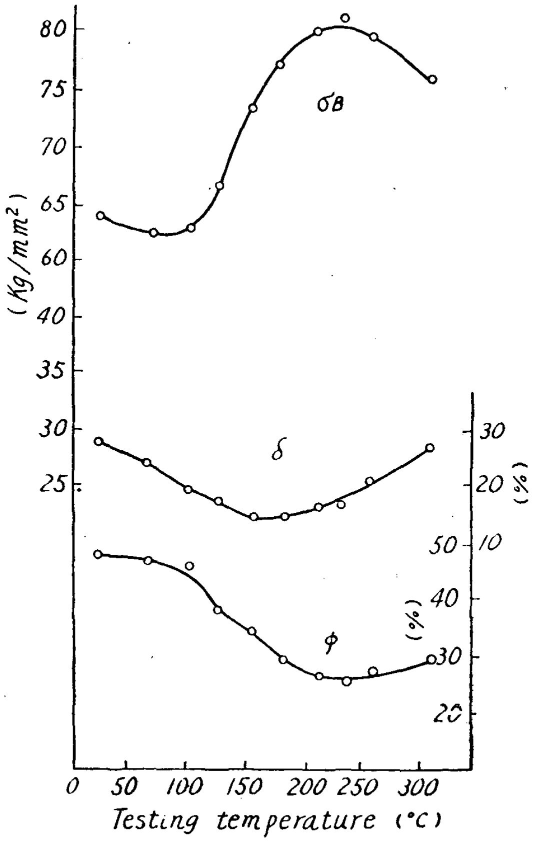

Fig. 28

Part B

As mentioned in Part A, the blue-brittleness was closely related with nitrogen, almost disappearing when the nitrogen content in ferrite becomes nil; further, with the increase of nitrogen content, the blue-brittleness became rapidly remarkable, and in pure iron it began to rise comparatively gradually with nitrogen content above about 0.008 per cent. It is, however, very difficult to decrease nitrogen content below 0.003 per cent. The following investigation was carried out with steels in which nitrogen was fixed with aluminium or with titanium to examine the change of blue-brittleness in low nitrogen side.

IV. Preparation of specimens and results of experiment

The specimens were prepared in the same way as described in Part A, except that the nitrogen fixation was made by aluminium or by low carbon Fe-Ti after deoxidation by silicon.

1. Effect of denitridation on steel containing 0.4 per cent of carbon and 0.7 per cent of manganese.

Steels containing 0.4 per cent of carbon and 0.7 per cent of manganese were made by adding a proper amount of nitrided manganese to the melt so that nitrogen content was 0.020 per cent. The steel 25 was oxidized only by 0.3 per cent of silicon, while the steel 26, after deoxidized by the above amount of silicon, was added 0.1 per cent of aluminium just before tapping the steel 25. The steel 27 was added 0.1 per cent more aluminum than that in the steel 26, and the steels 28 and 29 were added 0.15 per cent and 0.3 per cent of titanium, respectively, in stead of aluminium. In the Fe-Ti used here, aluminium was contained about one third as much as titanium. Table 5 shows the chemical analyses of these steels. The extremely low values of titanium in the steels 28 and 29 would be due probably to that nearly all titanium had become oxides and nitrides.

Table 5. Result of Chemical Analysis for low Manganese Steel.

	Chemical Composition Percent					
	C	Mn	Si	Al	Ti	N_2
No 25	0.38	0.70	0.25	non	non	0.018
No 26	0.40	0.75	—	(0.1)*	non	—
No 27	0.44	0.76	—	(0.2)	non	—
No 28	0.41	0.83	—	—	0.01 (0.15)	—
No 29	0.30	0.61	—	—	0.01 (0.3)	—

* ( ) is add percent at charge.

Figs. 29~33 show the experimental results for the steels 25~29. As seen from these figures, the blue-brittleness almost disappeared by the addition of aluminium or titanium. The beginning point of the blue-brittleness in the steel 25 was at about 80°, in the steel 26 at about 100°, and in the steels 27 and 28 with more aluminium or titanium at about 150°. The shifting of the beginning point towards high temperatures with the increase of fixed nitrogen would be due to the existence of manganese in steels as described in the previous report.

Particularly, in the steel 29 with 0.3 per cent of titanium, the blue-brittleness was hardly observable in the tensile strength, whereas it could clearly be observed both in the elongation and in the reduction of area, as shown in Fig. 34. The yield point somewhat increased in the range of blue-brittleness and the more the steels are denitrided, the more slightly it begins to increase.

The phenomenon of special importance was the discontinuous elongation after the yield point in the range of blue-brittleness. The serration was conspicuous

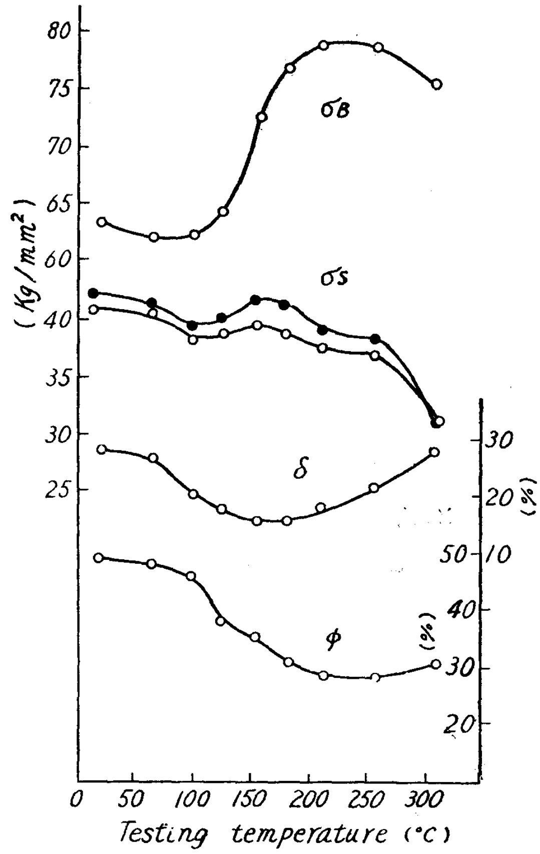

Fig. 29

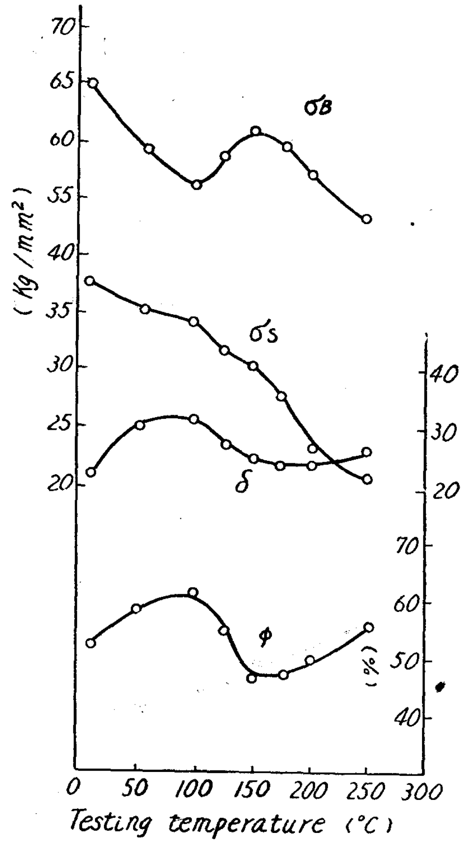

Fig. 30

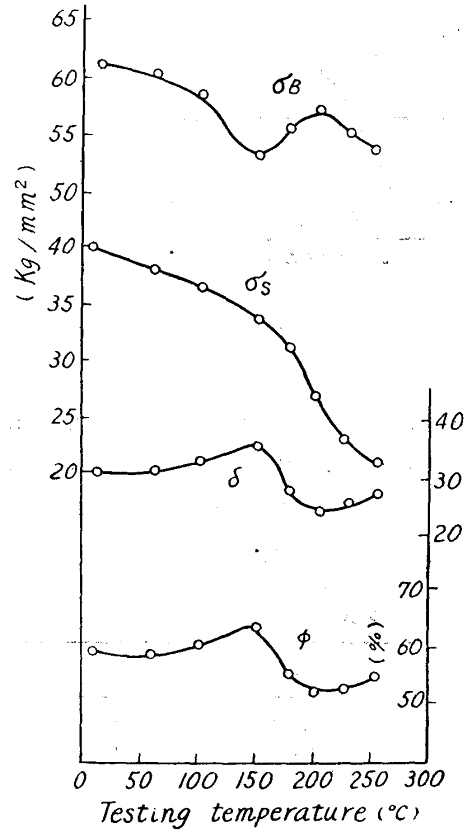

Fig. 31

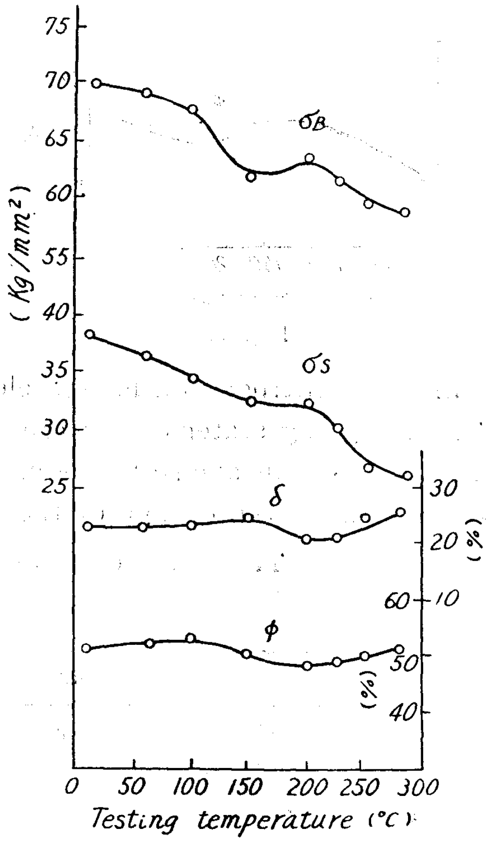

Fig. 32

in the steel 25, while in the other steels it was extremely small, being not at all observable in the steel 29. This would also indicate the gradual decrease of solid soluble nitrogen. The discontinuous elongation will be reported in detail in the subsequent papers.

The changes in the tensile strength, elongation and reduction of area were similar to those in Part A.

Fig. 34 shows the rate of increase in the tensile strength and the rates of decrease, respectively, in the elongation and reduction of area, in which the rate of increase in the steel denitrided by 0.3 per cent of titanium and 0.1 per cent of aluminium is negative, because this was calculated from the values at 150 and 200°, despite the fact that its tensile strength curve had no minimum point.

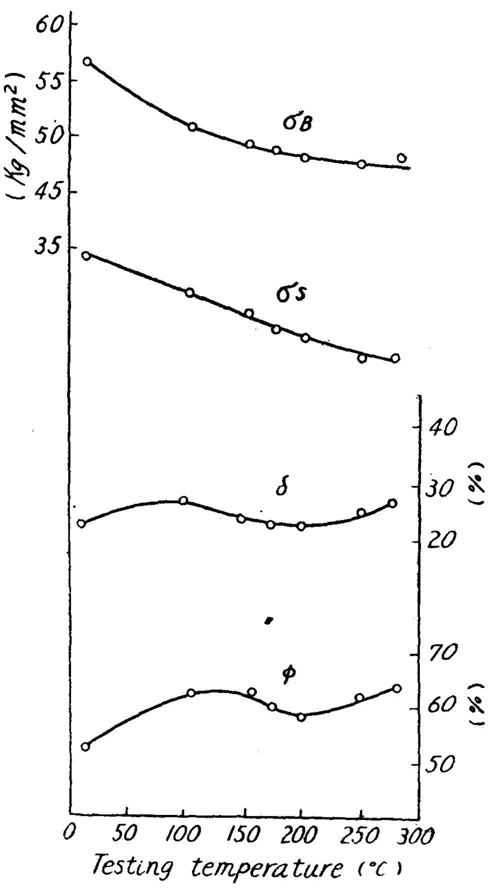

Fig. 33

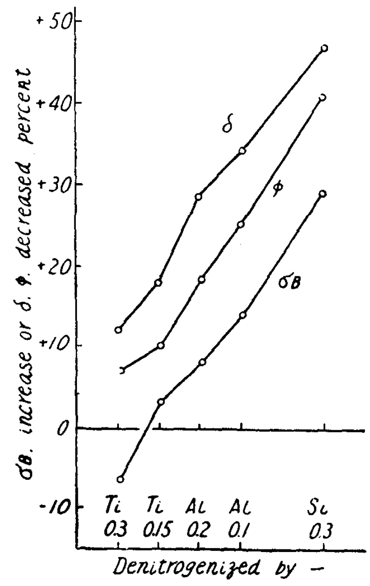

Fig. 34

2. Effect of nitrogen on melted electrolytic iron

The foregoing statements were the experimental results of the specimens containing carbon and manganese. Next, the following experiments were carried out to examine the change of the blue-brittleness in remelted iron denitrided.

Table 6. Result of Chemical Analysis for Iron.

	Chemical Composition Percent				
	C	Mn	Si	Al	N_2
No 30	0.027	tra	0.15	(0.3)*	0.035
No 31	0.031	0.00_2	0.22	(0.4)	0.042
No 32	0.030	tra	0.20	(0.2)	0.028
No 33	0.025	0.00_3	0.14	(0.5)	0.020

* ( ) is add percent at charge.

Table 6 shows the chemical compositions of the specimens used, in which the high content of nitrogen seems to be arose from nitrogen contained in AlN.

(a) The steels 30 and 31 were, after deoxidized by silicon, added 0.3 per cent and 0.4 per cent of aluminium, respectively, and then were casted within a few minutes, the results of which are shown in Figs. 36 and 37, respectively. As seen in these figures, the blue-brittleness almost disappeared, which was clearer than the case of the electrolytic iron mentioned in Part A. Table 7 shows the rate of increase in the tensile strength and the rates of decrease, respectively, in the elongation and reduction of area.

Table 7. σ_B increase or δ, ϕ decrease percent for No. 30 and No. 31.

	σ_B increase percent	δ decrease percent	ϕ decrease percent
No 30	14.5	38.0	11.8
No 31	10.0	44.3	37.0

If the curves shown in Fig. 7 are extrapolated toward low nitrogen side, it will be seen that, in steel 30 the rate of increase in the tensile strength and the rate of decrease in the reduction of area will correspond with each other, while the rate of decrease in the elongation will show a considerably large value, and that, in the steel 31, when the rate of increase in the tensile strength agree with that in Fig. 7, the rates of decrease in elongation and reduction of area become extremely different from those in Fig. 7, both showing high values. This is due to the high content of aluminium as will more clearly be seen in (b).

In the case of the electrolytic iron in Part A, the blue-brittleness began at about 70°, while in the case of steels containing lower nitrogen, it began at about 100°, the temperature being still raised when nitrogen content becomes extremely low.

(b) In the steels mentioned in (a), the tensile strength increased in the range of blue-brittleness. It was, however, probable that these steels should absorb nitrogen from air after adding aluminium. Hence, the specimens 32 and 33 were made by deoxidization and denitridation, adding 0.2 per cent and 0.5 per cent of aluminium to them, respectively, just before casting. Their results are shown in Figs. 37 and 38, respectively.

In these figures, it can be seen that the blue-brittleness, when measured by elongation, became smaller than those shown in Figs. 35 and 36 in which the steels were cast in a short time after adding aluminium. As aluminium was more added to the steels, the blue-brittleness began to decrease slightly. The same remark would also be applied to the cases of the steels 30 and 31.

This would show that aluminium, used as denitriding reagent, was more effective when added to the steels just before the solidification, and that the rate of absorbing nitrogen of molten steel from air became considerably high after denitriding them.

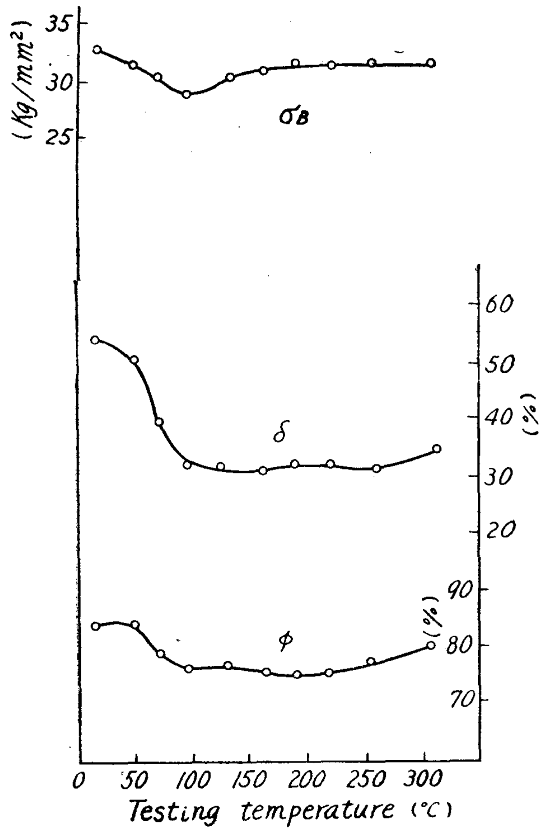

Fig. 35

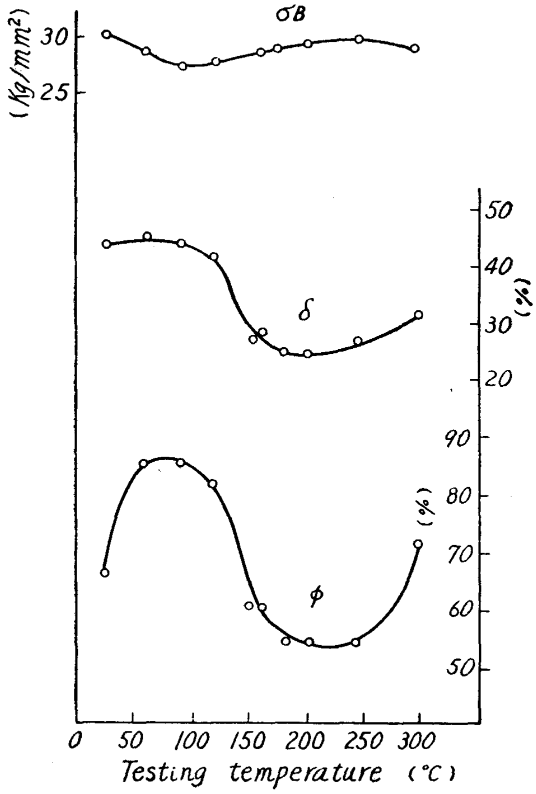

Fig. 36

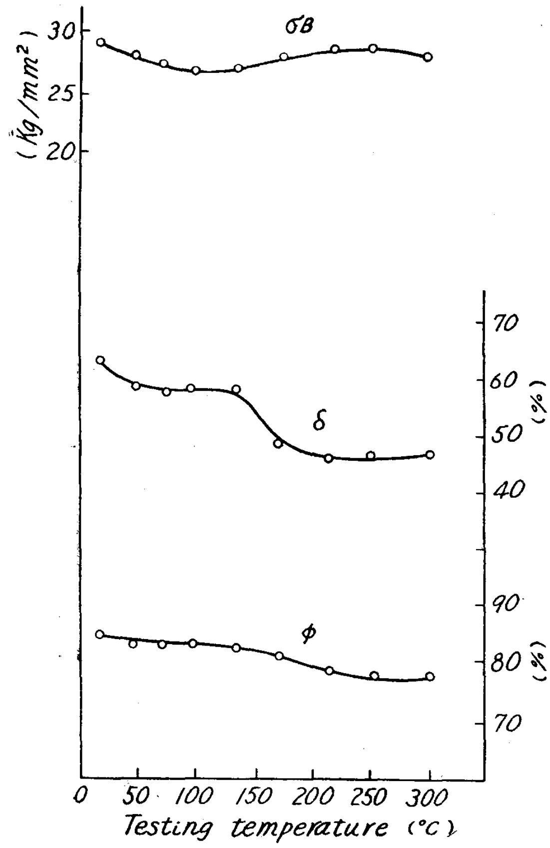

Fig. 37

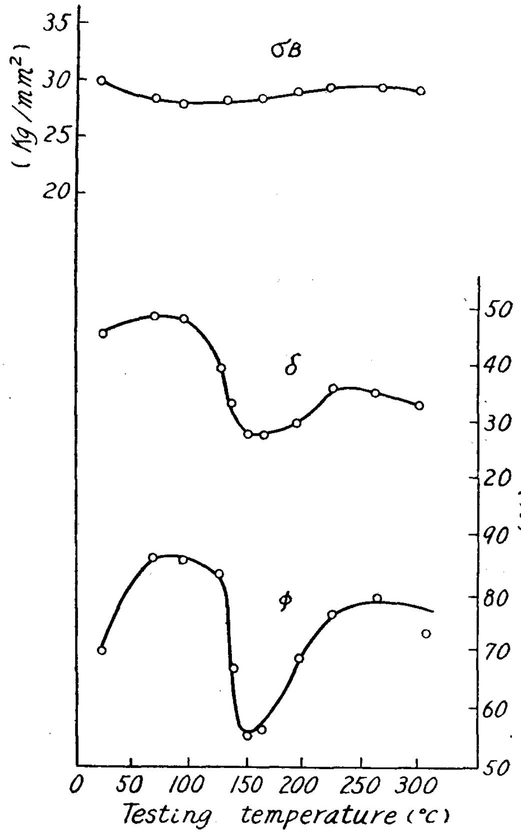

Fig. 38

Table 8 shows the rate of increase in the tensile strength and the rates of decrease, respectively, in the elongation and reduction measured from Figs. 37 and 38.

Table 8. σ_B increase or δ, ϕ decrease percent for No. 32 and No. 33.

	σ_B increase percent	δ decrease percent	ϕ decrease percent
No 32	7.4	27.5	7.2
No 33	5.8	43.5	35.3

If the values in Table 8 were adjusted to the rate of increase in the tensile strength in low nitrogen side shown in Fig. 7, it will be see that both rates of decrease of the steel 32 will find themselves on the extrapolated line, while those of the steel 33 shift far from it.

Table 9 shows the results of the investigation whether the rates of decrease, in the elongation and reduction of area find themselves on the values shown in Fig. 7 when the rate of increase in the tensile strength is fitted to the value on the curve of Fig. 7.

Table 9

	Al* ercent	σ_B increase percent	δ decrease percent	ϕ decrease percent
No 32	(0.2)	agree	agree	agree
No 30	(0.3)	agree	dis agree	agree
No 31	(0.4)	agree	dis agree	dis agree
No 33	(0.5)	agree	dis agree	dis agree

* ( ) is add percent at charge.

As seen from this table, the blue-brittleness, when measured by the change of the strenth, inconspicuous as aluminium content increase, but when measured by the change, respectively, of the elongation or of the reduction of area, it first decreased until aluminium coctent increased to 0.2 per cent and then began to increase severely with aluminum content. In this case, first the change of the elongation, and then that of the reduction of area deviate from those in Fig. 7. That is, the addition of aluminium up to 0.2 per cent was most effective in reducing the blue-brittleness and the more addition of aluminium reduced the change of the strength only slightly, but raisd severely the change, respectively, of the elongation and reduction of area. This may be seen to be connected with the fact that the more addition of aluminium than that necessary for deoxidation or denitridation reduces the elongation and necessarily the fatigue strength.

(c) On the steels denitrided and then made to absorb nitrogen

Aluminium and titanium having been added, the steels were made to absorb nitrogen again from air after appropriate time, and then the brittleness was examined.

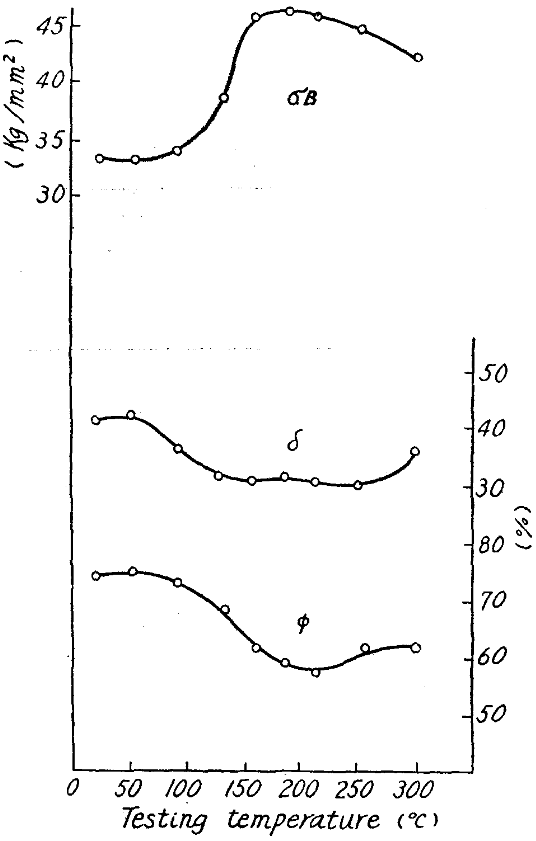

Fig. 39

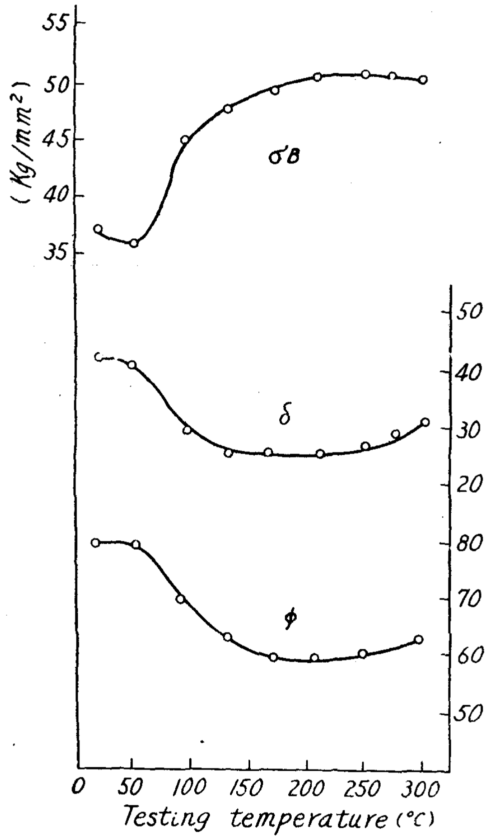

Fig. 40

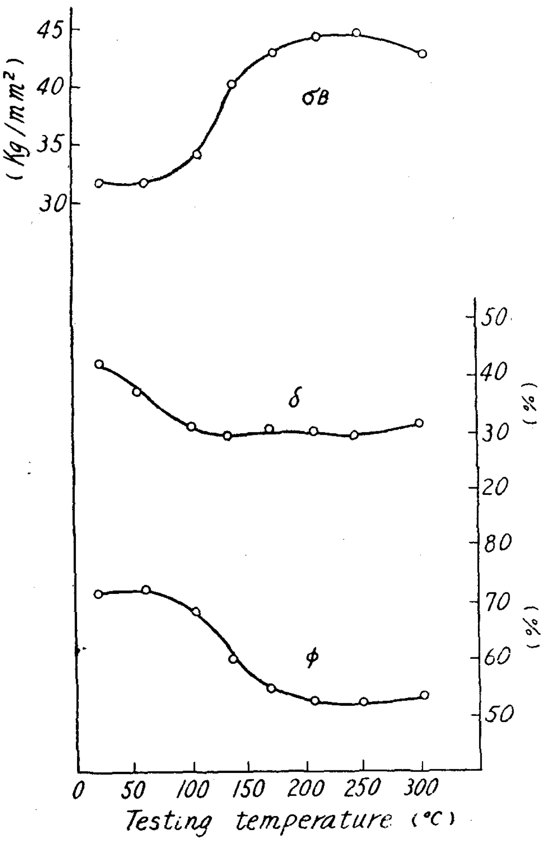

Fig. 41

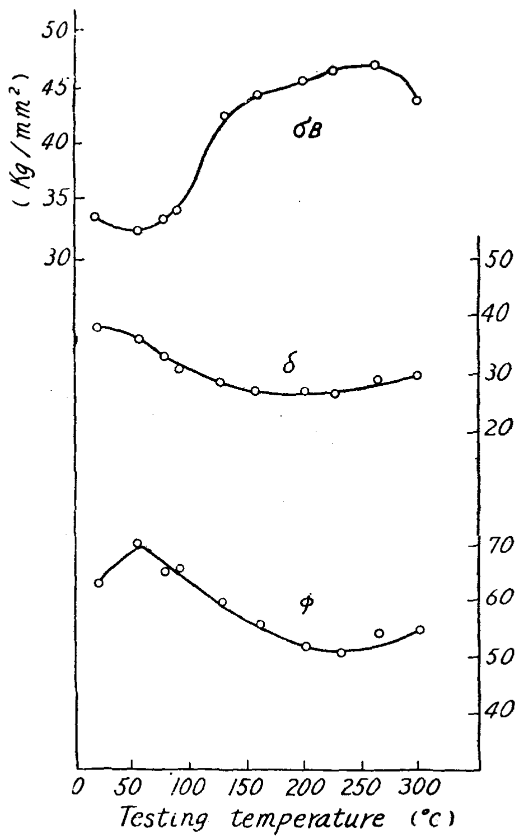

Fig. 42

0.15 per cent of aluminium was added to No. 34; 0.3 per cent of aluminium to No. 35; 0.15 per cent of titanium and 0.5 per cent of aluminium to No. 36; 0.3 per cent of titanium and 0.1 per cent of aluminium to No. 37. Table 10 shows the chemical analyses of these steels and Figs. 39~42 are the test results.

Table 10. Result of Chemical Analysis.

	Chemical Composition Percent					
	C	Mn	Si	Al	Ti	N_2
No 34	0.028	0.00_8	0.12	0.11 (0.15)*	non	0.022
No 35	0.027	tra	0.09_8	0.25 (0.3)	non	0.019
No 36	0.023	tra	0.14	—	0 (0.15)*	0.023
No 37	0.022	tra	0.17	—	(0.3)	0.022
No 38	0.029	0.00_8	0.12	0.23	non	0.034

* ( ) is add percent at charge.

The blue-brittleness in these steels was fairly remarkable as compared with those in Sec. 2, which means that the blue-brittleness begins to appear when steels re-absorb nitrogen after denitrided by aluminium or titanium.

Table 11 shows the rate of increase in the tensile strength and the rates of decrease, respectively, in the elongation and reduction of area. As seen in this table, these values of rates roughly corresponded to those in Fig. 7, except that, in the steel 35 denitrided by 0.3 per cent of aluminium, the change of the elongation was slightly large due probably to aluminium as previously mentioned.

Table 11

	σ_B increase percent	δ decrease percent	ϕ decrease percent
No 34	38.7	23.5	24.0
No 35	42.2	37.0	25.0
No 36	42.8	31.0	27.8
No 37	44.6	31.6	28.8

Further, the experiment was made with the steel 38, which was denitrided with manganese and silicon by usual melting method and to which 0.25 per cent of aluminium was added thereafter. The chemical analysis of this specimen is shown in Table 10 and the experimental results in Fig. 43.

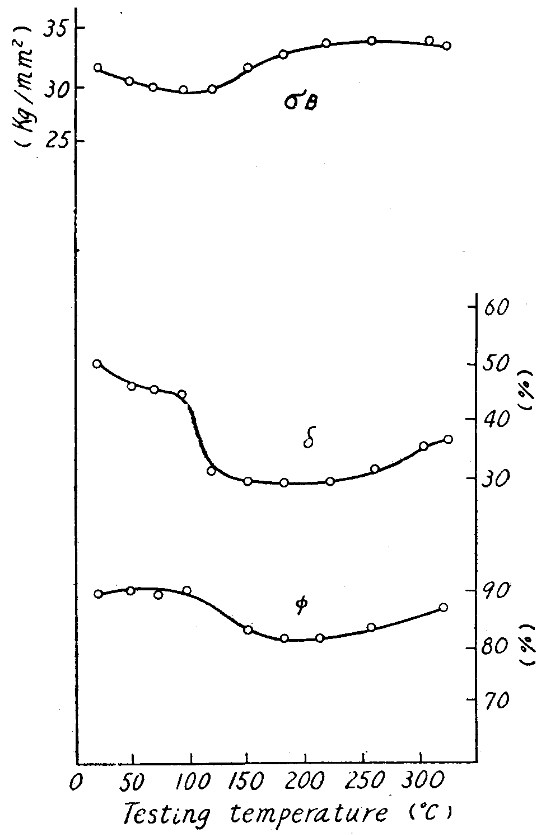

Fig. 43

As seen in this figure, the blue-brittleness became extremely small. The rate of increase in the tensile strength and the rates of decrease in the elongation and reduction of area are 13.5 per cent, 37.0 per cent and 9.8 per cent respectively.

The rate of decrease in the elongation was somewhat higher than that in Fig. 7 because of the addition of 0.25 per cent aluminum.

Thus, it will be seen that the experimental results mentioned above may also be applicable to usual case.

Summary

In order to ascertain the relations between the blue-brittleness and nitrogen, the condition of its occurrence was first examined by a tensile test at temperatures ranging over from room perature up to 350° and then the effect of nitrogen and finally those of aluminum and titanium used as denitriding reagent were investigated. The results obtained were as follows:

(1) The blue-brittleness was closely related with the nitrogen content; it occurred in steels containing dissolved nitrogen and could not be observable in steels free from nitrogen.

(2) In pure iron, the blue-brittleness rose rapidly with nitrogen content up to 0.008 per cent, and then comparatively slowly.

(3) By the presence of carbon, this range of rapid rise of blue-brittleness was narrowed.

(4) The blue-brittleness began to appear at about 70° and the maximum point of tensile strength moved toward high temperature side with the increase of nitrogen content. The blue-brittleness, when measured by the change of elongation, appeared at lower temperature than when measured by the change of tensile strength or by reduction of area.

(5) The blue-brittleness was reduced by the presence of manganese, but with the increase of nitrogen content, it clearly appeared and its beginning point moved toward low temperature side.

(6) In steels with low nitrogen, the blue-brittleness was slowly recovered by heating, while in steels with high nitrogen the recovery was comparatively rapid.

(7) When steels were denitrided by aluminum or titanium, the blue-brittleness almost disappeared and completely vanished when free nitrogen became nil.

(8) It was impossible to remove completely the blue-brittleness in elongation by adding aluminum to remelted electrolytic iron. This was due probably to a minute content of carbon in it.

(9) By the addition of aluminum up to 0.2 per cent, the blue-brittleness was reduced, while, in steels denitrided by more than 0.2 per cent of aluminum, it became large both in elongation and reduction of area due to the severe local contraction with the increase of aluminum content.

(10) Titanium was a more effective denitriding reagent than aluminum.

(11) The decrease of the blue-brittleness due to aluminium or titanium was caused by the fixation of nitrogen in steels.

In conclusion, the present investigators wish to express their gratitude to Dr. Takejiro Murakami for his encouragement.