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On Various Properties of Nodular Graphite Cast Steel*

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Synopsis

This paper describes at first the outline of the theory of high grade cast iron manufacturing that has been clarified by one of the authors through a fundamental study of the relation between cast iron and its oxygen contents. In place of the relation between the oxygen content of cast iron and its qualities, the relation between tensile strength in cast state and variation of structure was examined. A little difference in the degree of deoxidation of cast iron was indistinguishable by analysed oxygen content. To grade the qualities according to the variation of structure is the most accurate and simplest method.

When nodular graphite hyper-eutectoid cast steel containing less than 1.7 per cent carbon is produced the theoretical foundation for determining carbon and silicon contents is to choose the reciprocal relation between the points on the line $E\gamma$ or in the lower areas under the line $E\gamma$ in the basic projection diagram of the Fe-C-Si system.

According to this theory, an investigation of the various properties of nodular graphite hyper-eutectoid cast steel was carried out. The results obtained can be summarized as follows:

(1) This cast steel does not call for so careful selection of materials, and is of higher value in mechanical properties than those of DCI, malleable iron and cast steel.

(2) Since this metal has far better castability than cast steel and DCI, it is possible to manufacture castings of thin section and complicated shape.

(3) Compared with gray cast iron and malleable cast iron, this cast steel is very useful for electric and magnetic material.

(4) Wear resistivity of the pearlitic type of this metal is far superior to any of the ordinary cast iron, pearlitic cast iron and DCI. Wear resistivity of the ferrite type is the same as that of DCI, but it is far superior to the black heart malleable cast iron.

(5) This cast steel is material that has excellent property for induction surface hardening, even in the case of ferrite type, and after heat-treatment it has the about $40\sim50\ R_C$ in the surface hardness.

The Jominy hardness curves of nodular graphite cast steel were measured. Compared with the pearlite type, cast steel of ferrite type has low quench-hardness because of its carbon concentration in austenite.

I. Introduction

Ductile cast iron (DCI) treated with magnesium has been invented, which is of the highest quality as cast iron. However, its weak point in industrialization is that requires strict selection of raw material. Therefore, in manufacturing, it is desirable to invent high quality cast iron which does not call for strict selection of raw material which is castable into complicated shapes and which has good mechanical properties the same as or superior to those of DCI, malleable

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cast iron and forged steel.

Basing upon the fundamental study of the relation between cast iron and its oxygen content, one of the present authors found a method of manufacturing hyper-eutectoid graphite cast steel (or forged steel) containing less than 1.7 per cent carbon and less than 6 per cent silicon, and it has been industrialized already. In classifying this cast steel from the viewpoint of the carbon content, it may be said that it is in hyper-eutectoid range, compared with the spheroidal graphite cast iron containing magnesium and cerium, while in cast state, it is spheroidal graphite cast steel(1). Moreover, only from the viewpoint of the carbon content, Tantiron (C–0.75~1.25 per cent, Si–14.0~15.0 per cent) and Durriron (C–0.2~0.6 per cent, Si–14.0~14.5 per cent) are steel, but they are called acid-proof cast iron because they contain graphite in cast state: similarly, this cast steel can be called spheroidal graphite cast iron. In this study some properties of hyper-eutectoid spheroidal graphite cast steel will be given.

II. Relation between properties of the cast iron and its oxygen content

One of the present authors systematically examined by the super-heated melting, vacuum melting and other methods the relation between the properties of cast iron and its oxygen content. From the results, the heredity and the theory of manufacturing high strength cast iron were clarified. Fig. 1 shows the relation between the oxygen content of cast iron and its qualities, for example, the relation between tensile strength in cast state and variation of structure. The horizontal axis refers to the oxygen content, but the analyzed oxygen content cannot indicate accurately the quality of the material, that is, a little difference in the degree of deoxidation in cast iron is indistinguishable by analyzed oxygen content. It is the most accurate and simplest method to grade the quality of material (concerning the oxygen content) according to the variation of structure.

Next, it is generally said that the property of cast iron, e.g., heredity, is affected not by the chemical composition such as carbon, silicon, manganese, phosphorus and sulfur, but by the oxygen content. (And too, affected by the minute metallic element contained such as antimony, tin, lead, bismuth etc.) The industrialized cast iron having similar composition may be classified according to the degree of their oxygen content, as shown in the lower column in Fig. 1.

The electric-furnace cast iron produced with the oxidizing acid slag and basic slag has small graphite size such as eutectic graphite for its characteristic; it is stronger than cupola-melted cast iron, but is brittle and poor in fluidity and of inverse chill. These weak points are due to its large oxygen content. These tendencies are especially remarkable in the basic electric-furnace cast iron. The quantity of oxygen content depends upon the degree of the skill in reducing-

(1) M. Homma, J. Japan Inst. Metals, **21** (1957), A-374: Japanese Patent, Nos. 231087, 229605.

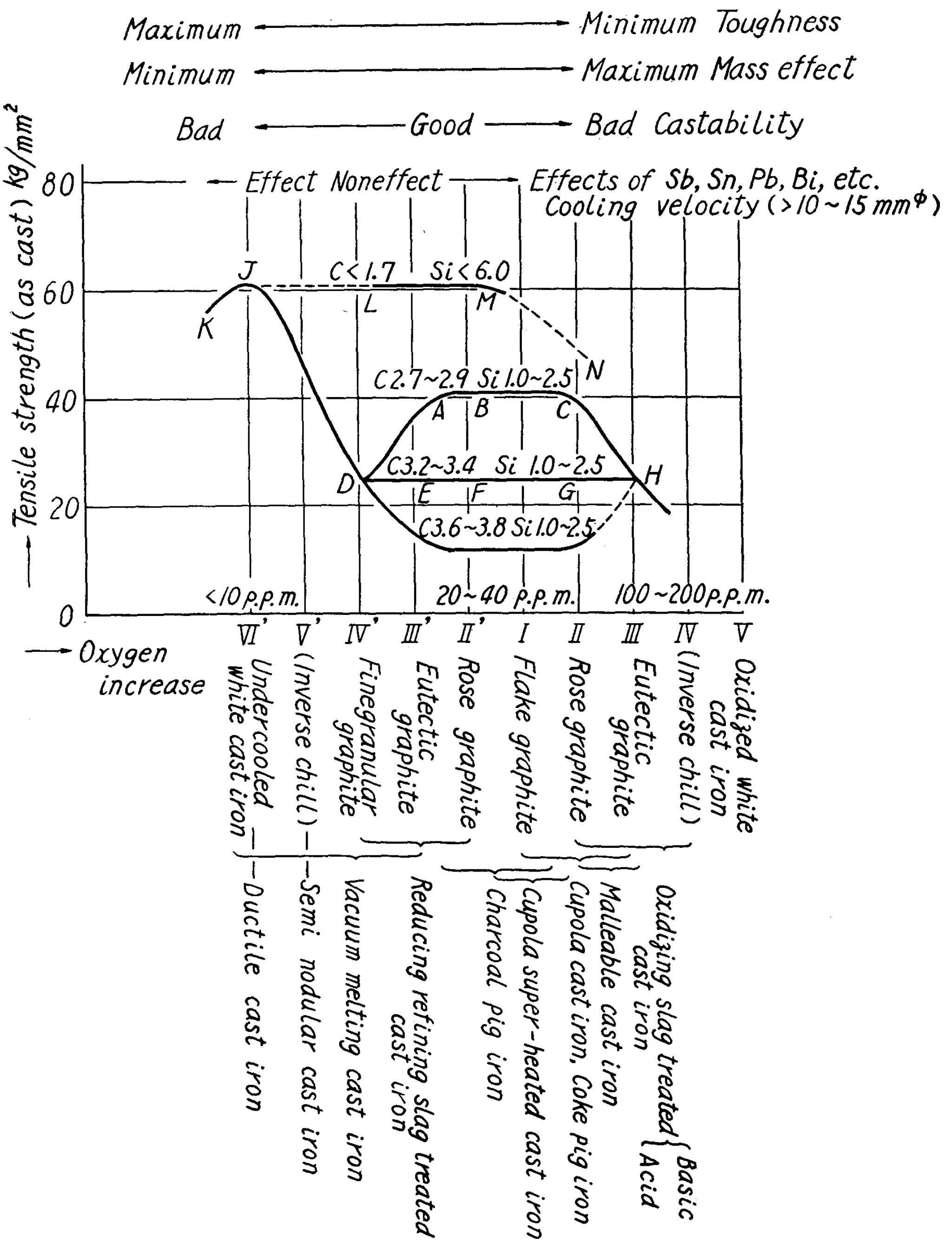

Fig. 1. Relationship between various properties of cast iron and its oxygen contents. (M. Homma).

refining method by slag, so it should be noted that the large oxygen content is not the weak point inevitable electric-furnace cast iron.

Cupola-melted cast iron is better to electric-furnace cast iron in oxidation resistivity, in toughness, in fluidity and in the graphite form which easily becomes more flaky than the latter. High temperature melting (1500~1600°C) cupola cast iron is theoretically more deoxidized than low temperature melting one. This is the case with melting in non-oxidizing atmosphere, but not in oxidizing atmosphere like cupola melting. In spite of the high tapping temperature, the oxygen content of cupola melting cast iron seems to be in the range between I~III in Fig. 1. It is difficult to distinguish charcoal pig iron from coke pig iron by means of their analyzed oxygen content. However, from the theoretical point of view, it may be said that the former is more deoxidized than the latter, or it is clear from the slight difference in their microstructures that the former is more deoxidized than the latter.

The smaller oxygen content, is the smaller the mass effect is, i.e., the change in graphite form due to the cooling velocity decreases with the decrease of oxygen content, or probably the self-hardening will take place in the pearlite matrix. Therefore, in manufacturing flake graphite cast irons (the parallel parts of III', II'~II and III in Fig. 1), especially fine flaky (wormy flaky) graphite high-strength cast iron with the material having a small value of Sc, the mass effect decreases according to the numbers on the left hand side (III', II') in the figure and industrialization of high strength cast iron with higher toughness and wear resistivity is possible without Ca-Si and without Fe-Si inoculation.

The effect of minute metallic elements, e.g., antimony, tin and lead etc. which partly affect the heredity of cast iron, does not appear in the cast irons in the range of IV'~V in the figure, while it appears in those in the range, of above V' whose oxygen content is small. That is, the super-cooled white cast iron due to the low oxygen content is unable to co-exist with these minute metallic elements' etc, e.g., the coke pig iron containing fairly large amount of antimony and tin hardly produces super-cooled white cast iron in the cast of deoxidizing melting by vacuum treating. From this fact, magnesium-treated DCI is considered to be a melt deoxidized so as to be super-cooled white cast iron and graphitized by Fe-Si. It is clear from the above reason why it is hard to manufacture DCI from raw coke pig iron.

The above-mentioned is the case of cast iron containing 2~4 per cent of carbon with eutectic constituents.

On the other hand, the hyper-eutectoid graphite cast steel containing spheroidal graphite in cast state of less than 1.7 per cent carbon content, is not affected by these minute metallic elements. This means that in manufacturing it the influence of the raw material on the quality of the products is little.

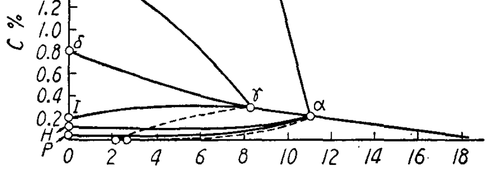

Fig. 2. Basal projection of Fe-C-Si diagram.

The above-mentioned nodular graphite cast steel is manufactured debased on the results of fundamental studies shown in Figs. 1 and 2. In oxidation melting of this cast steel, Fe_3C and flake graphite are apt to be produced, and the expected products cannot be obtained. The theoretical basis of determining carbon and silicon content is to choose the reciprocal relation between the points on the line $E\gamma$ or in the lower area under the line $E\gamma$

in the basic projection diagram of the Fe–C–Si system shown in Fig. 2. (The maximum carbon solubility point of austenite E moves along the line $E\gamma$ with the increase of silicon content, and vanishes at point γ.)

III. Improvement of melting and after-treatment

In the past improvement in the quality of cast iron was made by adjusting elements contained, i.e., carbon, silicon, manganese, phosphorus and sulfur, or by adding other elements such as nickel and chromium. To-day, improvement is made or removing by adding a very small amounts of other elements and a method for achieving this purpose has been established by the treatment after tapping.

As after-treatment, processes of addition, inoculation and injection of Fe–Si, Ca–Si, Fe–Si–Ca–Mn(Cr)[(2)], Mg alloy, Misch metall and CaC_2 are known. These treatments are all carried out for the purpose of controlling oxygen content. They are effective in improving melt, though they are accompanied with bad effects such as instability of momentary reaction, unavoidable falling of temperature with the increase of the additional amount, and mixing of slag and gases.

To improve the melting of cast iron the high temperature cupola-melting, reducing-refining by slag and duplex melting processes are in use, and above-mentioned treatment after tapping is mostly used to-day. If a reducing melting in the furnace which is based on the above-mentioned fundamental studies is adopted, the after-treatment is unnecessary, or it will be sufficient to add a very small amount of additionals compared with the treatment after tapping of oxidized melt. No doubt this reducing melting will be suitable[(3)] for industrialization of the manufacture of DCI, high strength cast iron and hyper-eutectoid cast steel.

The future problem desirable is to investigate how to control the properties of the melt in the furnace.

IV. The cast structure of nodular graphite cast steel

When this cast steel is melted in oxidized atmosphere, a small amount of graphite and large amount of cementite remained. The form of the graphite becomes worse and the amount of the graphite decreases with the progress of oxidation of the melt. The castability becomes worse with the progress of oxidation, and in the case of very highly oxidized melt, it turns white iron (the hyper-eutectic structure without graphite) in spite of strong inoculation.

In the case of suitable reduction melting, cementite does not exist in the cast structure, only spheroidal graphite and pearlite remaining, and the cast steel had a high tensile strength; and when silicon is added with much amounts, it becomes bull's eye cast structure and increased elongation. In the case of the excessive deoxidized melting, e.g., the melting by magnesium or calcium treat-

(2) Kusaka, Japanese Patent, Nos. 1364, 1827 (1957).
(3) M. Homma, H. Meguro, Y. Abe and R. Ohno, Imono, **30** (1958).

ment, the melt is highly super-cooled, and in the cast structure increases the cementite.

When the minute metallic elements such as alkali, alkali earth, magnesium and boron co-exist in the iron, the tendency to increase the roundness of the circumference of graphite is seen, but this irregularity of the circumference of graphite has few effects on the elongation and other properties of the material.

Nodular graphite cast steel can be produced by the magnesium treatment method(4) with the material of the compositions similar to the above. However, by the magnesium treatment method, the castability is bad even when the degree of the carbon saturation is above 1. It will be much worse in the case of industrial manufacturing of the material containing hyper-eutectoid carbon by magnesium treatment and many difficulties are expected in the point of castability.

V. Forginability of nodular graphite cast steel

A graphite forged steel named "Graphitic Steel"(5) is industrially manufactured in U.S.A., which has composition similar to the above mentioned cast steel. This forged steel is manufactured first by making it into steel ingot in the absence of graphite, and after forging and rolling, it is made by graphitized annealing. It is reported(6) that a study has been made on the manufacture of graphite cast steel in the absence of graphite in cast state, being graphitized by annealing.

The present nodular graphite cast steel can also be produced, not by casting, but by making ingot containing spheroidal graphite in the cast state, and then by forging and rolling, without the graphitized annealing process.

The microstructure of this steel is shown in Photos. 1 and 2. In the case of

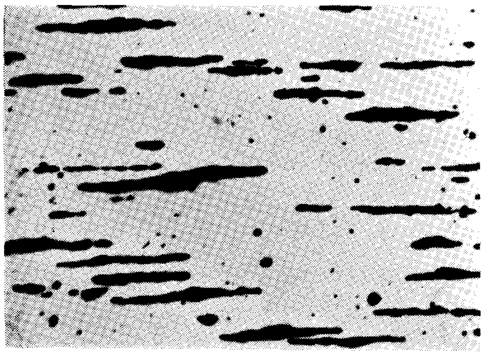

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Photo. 1. Transverse section of nodular graphite forged steel. (reduction degree 95%).

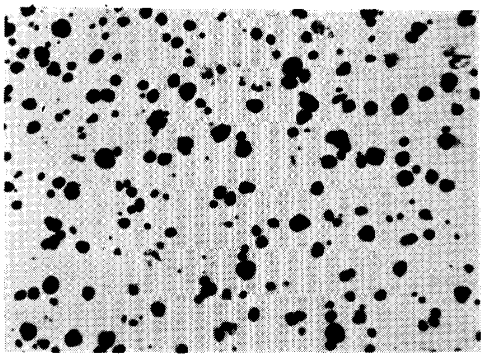

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Photo. 2. Longitudinal section of nodular graphite forged steel. (reduction degree 95%).

forging into a cylindrical bar, the form of the graphite in the transverse section is spheroidal (Photo. 1), and in the longitudinal section it is flaky (Photo. 2).

(4) K. D. Millis, A. P. Gagnebin and N. B. Pilling, Japanese Patent, II, No. 313 (1953)
(5) A. F. Sprankel, Iron Age, **169** (1952), 1-100; 3-108.
T. Satô and S. Toya, J. Japan Inst. Metals, **18** (1854), A-107.
(6) T. Satô and S. Toya, J. Japan Inst. Metals, **21** (1957), 234.

The hardenability, graphite form, hardness and general mechanical properties of these hyper-eutectoid graphitic forged steels will be reported in detail in a paper to follow.

In the casting or ingot of the nodular graphite cast or forged steel and "Graphitic Steel", the former contains graphite, but the latter does not. Consequently, the former does not require the graphitized annealing process. As to the latter, in order to avoid the precipitating of graphite in the rolling and forging processes before graphitized annealing, it is necessary to keep the silicon content below a certain quantity. The reason why such difference exists between the melting process of the above two cast steels is to be found in the difference of the melting methods as mentioned above, that is, the former is produced by the reduction melting method and the latter is by the oxidation melting method.

VI. The mechanical properties

The nodular graphite cast steel is better than DCI in many points; it is not affected by the raw material and has good mechanical properties, i.e., high tensile strength, high impact value and high fatigue endurance limit, and good forginability.

Table 1 shows a part of the mechanical properties of various types of this steel, and Photos. 3~6 show their microstructures. As seen from the table, both ferrite and pearlite types of this steel are the same as the malleable cast iron in elongation, but this cast steel is 10~15 kg/mm² higher than the latter in tensile strength, and also higher in impact value and fatigue endurance limit. Moreover,

Table 1. Mechanical properties of nodular graphite cast steel.

Property \ Kind		Pearlitic type	Bull's eye type	Spheroidized pearlitic type	Ferritic type
Tensile strength	kg/mm²	60~ 70	55~ 65	58~ 65	45~ 58
Yield point	kg/mm²	50~ 60	40~ 47	40~ 45	38~ 44
Elongation	%	1~ 3	3~ 7	7~ 13	13~ 20
Bending		10~ 30	30~ 60	110~140	over 160~180
Compression strength	kg/mm²	160~210	140~180	—	—
Compression yield point	kg/mm²	—	—	50~ 65	50~ 70
Charpy impact value	Unnotched kgm/cm²	4~ 9	5~ 10	8~ 15	14~ 20
	notched kgm/cm²	0.6~1.0	0.6~1.2	1.5~2.2	2.0~3.0
Hardness B.H.N.		260~280	210~220	220~240	130~140
Fatigue limit	kg/mm²	—	—	—	22~ 23

test piece for bending 10×16×230 mm
test piece for compression strength 14ϕ×25 mm.

Photo. 3. Pearlitic type of nodular graphite cast steel.
tensile strength 73.5 kg/mm²
yield point 50.5 kg/mm²
elongation 1.5 %

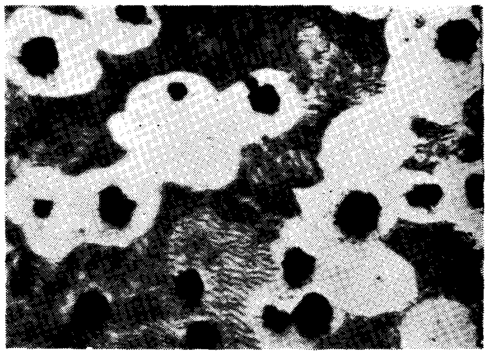


Photo. 4. Bull's eye type of nodular graphite cast steel.
tensile strength 61.8 kg/mm²
yield point 42.3 kg/mm²
elongation 5.0 %

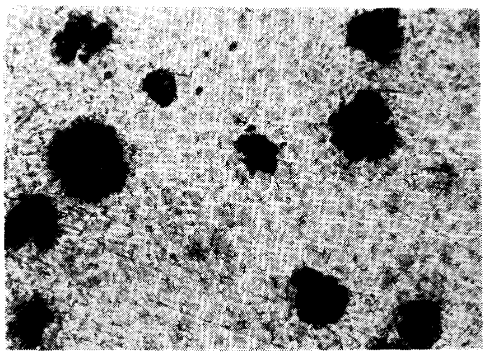


Photo. 5. Spheroidized pearlitic type of nodular graphite cast steel.
tensile strength 62.4 kg/mm²
yield point 44.8 kg/mm²
elongation 11.8 %

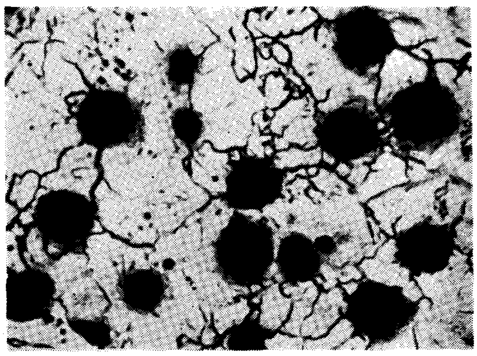


Photo. 6. Ferritic type of nodular graphite cast steel.
tensile strength 54.0 kg/mm²
yield point 42.3 kg/mm²
elongation 15.2 %

the shortening of the annealing time to below 1/5, the free thickness in casting, the easy inoculation and the possibility of the improvement in mechanical properties by alloying with chromium, molybdenum or tungsten are big merits of this cast steel, which are impossible with malleable cast iron. Black heart malleable cast iron is now manufactured in the grade of Japanese industrial standard (JIS) No. 3 (tensile strength of 35 kg/mm^2, elongation of 10 per cent). This cast steel may be considered to have the higher mechanical properties which correspond to those of JIS No. 4 or No. 6. However, it is a weak point of this cast steel that its casting temperature is higher than those of DCI and malleable cast iron.

As this nodular graphite cast steel is better to the ordinary cast steel (containing no graphite) and the forged steel in the mechanical properties, it can be used in place of the latter ones. It has the lower casting temperature, better casting surface, and greater capability of thin section being cast into complicated shapes than those of the ordinary cast steel; and compared with forged steel, it has lower manufacturing cost owing to the absence of the forging process. Its impact value is similar to that of hyper-eutectoid forged steel, e.g., tool steel (annealed), but it is lower than those of low carbon cast steel and forged steel.

VII. Hardenability and high frequency induction hardening tests

1. Hardenability

The hardenability curves of this cast steel were obtained by using standard Jominy test pieces and hardening apparatus. The chemical composition and the process of the heat-treatment of the test pieces of nodular graphite cast steel are shown in Table 2. The test pieces, after heat-treatment suitable for each type,

Table 2. Chemical composition and the process of heat-treatment of Jominy test pieces.

Mark of specimens	Kind	Chemical composition %					Heat-treatment
		C	Si	Mn	P	S	
a	Pearlitic type	1.57	2.50	0.25	0.011	0.005	900°C·3H → 750°CA·C
b	Ferritic type						850°C·2H → 750°C·6HF·C
c	Pearlitic type	1.52	2.38	0.24	0.011	0.014	900°C·3H → 750°CA·C
d	Pearlitic type						//

were hardened at 850°C for 30 minutes and the hardenability curves are shown in Fig. 3. From these curves it is seen that the hardness of sorbitic pearlite type differs from that of ferrite type, which seems to depend on the difference of concentration and diffusion distance of the carbon in austenite.

It is reported the hardening temperature suitable for DCI is 880~900°C; in the case of pearlite matrix, heating at 880°C for 15 minutes per inch thickness is sufficient, and in case of ferrite matrix, heating at 880°C for 30 minutes[7] per inch thickness will be necessary.

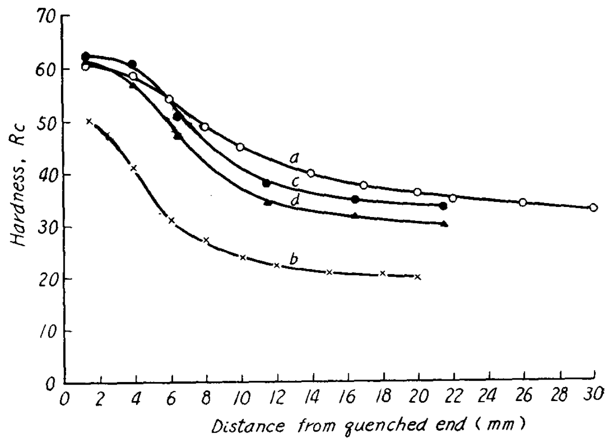


Fig. 3. Hardenability curves of nodular graphite cast steel.

2. High frequency induction surface hardening test

Nodular graphite cast steel of any type, pearlite, bull's eye, sorbitic pearlite or ferrite type can be treated by high frequency induction surface hardening.

(i) Pearlite and bull's eye types

Materials, preliminarily heat-treated suitably for each type, were cut into 30~20 mm cylindrical bars, whose chemical compositions and heat-treatments before hardening are shown in Table

(7) Hayashi, Sugihara and Nakazawa, Kinzoku, **27** (1957), 211.

3. The condition of high frequency induction surface hardening was as follows:

Table 3. Chemical composition and heat-treatment before high frequency induction surface hardening.

Kind	Chemical composition %					Mechanical properties			Heat-treatment
	C	Si	Mn	P	S	Tensile strengh, kg/mm^2	Elongation, %	Hardness BHN	
Pearlitic type	1.52	2.38	0.24	0.011	0.014	67.0	2.0	269	900°C·3H → 800°CA.C
Ferritic type						56.0	7.7	200	900°C·3H → 750°C.·6HF.C

Primary voltage was 3100V, primary current 32～35A, secondary capacity 40～45KV, diameter of coil 31 mm, hardening temperature 860～900°C, heating time 1～8 minutes and cooling time 10 minutes.

The results of the high frequency induction surface hardening tests are shown in Table 4. The hardness of bull's eye type is a little lower than that of pearlite type. For reference, the surface hardness after hardening of Si-Mn cast steel 2B (C-0.40～0.50 per cent, Si-0.50～0.60 per cent and Mn-0.09 1.10 per cent) is Rc 50～52, and that of Si-Mn cast steel 3B (C-0.50～0.60 per cent, Si-0.50～0.60 per cent and Mn-0.90～1.10 per cent) is Rc 58～60.

Table 4. High frequency induction surface hardening tests.

Kind	Pearlitic type		Bull's eye type	
Hardness	R_C	H_S	R_C	H_S
Before hardening	～	38	～	35
Surface after quenching	63	80	59	75
1 mm inner part from surface	61	～	49	～
2 mm inner part from surface	57	～	45	～
3 mm inner part from surface	31.2	～	23	～

Further, hardening was repeated several times and its aptitude as the high frequency induction material was examined, and the results are shown in Table 5. This nodular graphite cast steel is better than Si-Mn cast steel 2B as hardening

Table 5. Repeated hardening tests with high frequency induction furnace.

Specimens	Heat-treatment before hardening	Repeated hardening number until crack occurrence
Nodular graphite cast steel pearlitic type	900°C·3H	5～7
Nodular graphite cast steel Ferritic type	900°C·3H → 700°C·6H	7～8
Si-Mn steel 2B	900°C·3H	5～6
Si-Mn steel 3B	900°C·3H	3～4

material.

(ii) Ferrite type

Two or three manufactures of ferrite type cast steel were examined by high frequency induction surface hardening test to see whether high hardness can be obtained by a short time heating or not, and the results are shown in Table 6.

Table 6. High frequency induction hardening tests of ferritic type.

Manufacture	Specimen No		Coil	Load KW	Time sec	Hardness R_C
Tap fork	1	Right Left	Inner dia 25 mmϕ	7.8	30	47 50 48.5, 54
	2	Right Left	Length 17 mm	9.8	20	49.5, 52 48.5, 43
Low fork	1	Right Left	〃	13	13	41, 45, 47 43, 47, 49
	2	Right Left		13	13	42, 49, 52 52, 51, 52
Center guide piece	1	Right Left	Inner dia 11 mmϕ	8	105	56, 49 54, 50
	2	Right Left	Length 123 mm	10	30	43, 40 45, 37
Guide piece	1	Right Left	〃	9	60	50, 37 50, 33
	2	Right Left		9	60	50, 37 50, 37

When suitable input and heating time were given, the surface hardness of above Rc 40 could be obtained even in the case of ferrite. Some irregurality in hardness value seems to be due to imperfection of heating coil and jig.

VIII. Magnetic properties

The magnetic properties of ferrite type nodular graphite cast steel are as follows: Its chemical composition is shown in Table 7, and its magnetic properties in the case of the maximum magnetic induction of Bm 10,000 gauses are shown in Table 8. The curve B-H is shown in Fig. 4, the hysteresis curves in

Table 7. Chemical composition.

No	C	Si	Mn	P	S	Raw material
621	1.59	2.02	0.43	0.040	0.015	Pig iron+Steel scrap
622	1.37	2.62	0.36	0.017	0.004	Steel scrap

the case of the maximum magnetic induction of Bm 10,000 gauses are shown in Fig. 5. As seen from the figures, the nodular graphite cast steel of ferrite matrix is higher than high silicon (Si 2.5~3.0 per cent) gray cast iron as cast state in permeability (about ten times) and the former is far lower than the latter in coercive force (about 1/6 of the latter) and also lower in hysteresis loss (about 1/10); these properties show that the nodular graphite cast steel is very suitable for electric and magnetic material.

Table 8. Magnetic properties of nodular graphite cast steel.

No		μ_0	μ_m	Br	Hc	Hysteresis loss Wh	
						erg/cm³/cycle	W/lb
621	(1)	180	1900	7960	2.23	6940	2.52
	(2)	160	2200	8120	2.20	6540	2.37
	(3)	160	1300	7900	2.10	6600	2.40
622	(1)	220	2100	8220	2.06	6340	2.30
	(2)	190	2100	7910	2.08	5750	2.09
	(3)	140	1700	7940	1.84	6230	2.26

note μ_0 : Initial permeability.
μ_m : Max. permeability.
Br(gauss) : Residual magnetic induction.
Hc(oersted) : Coercive force.

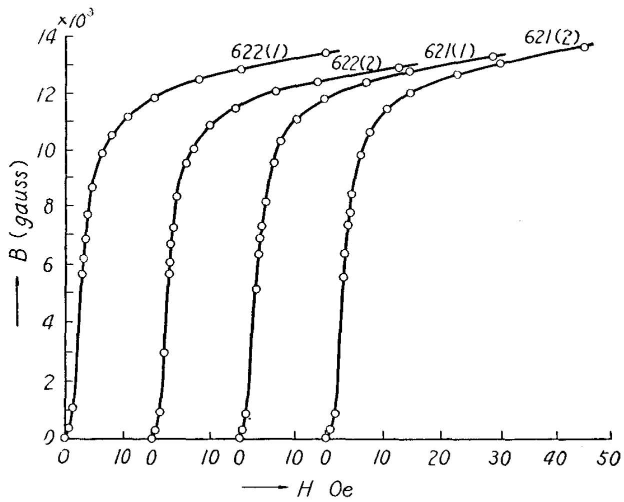


Fig. 4. Magnetized curves of nodular graphite cast steel.

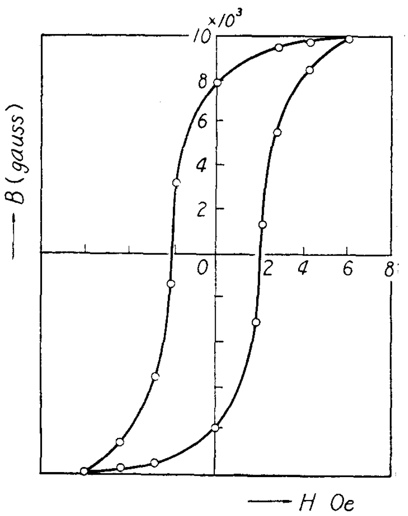


Fig. 5. Magnetic hysteresis loop of nodular graphite cast steel.

IX. Fatigue limit and impact test

1. Fatigue limit of ferrite type cast steel

By using the rotary bending fatigue testing machine of Ono type, the fatigue limits of nodular graphite cast steel (SN) and black heart malleable cast iron (M) of ferrite matrix were examined. The test piece unnotched was 10 mm in diameter at the parallel part and 15 mm in diameter at the handle. The chemical composition, the tensile strength and the annealing cycle are shown in Table 9, and the results of fatigue tests in Fig. 6.

The fatigue limit of ferrite type nodular graphite cast steel was 22.4 kg/mm² and that of black heart malleable cast iron was 18.3 kg/mm₂ or 18.5 kg/mm². As to the repeated number of fracturing of horizontal bar, in the case of the fatigue endurance limit of 25.5 kg/mm², it was 1.06×10^5 or 1.09×10^5 for black heart malleable cast iron, and 4.9×10^5 for nodular graphite cast steel. The higher

Table 9. Chemical composition and mechanical properties.

Mark	Chemical composition %						Mechanical properties			Microstructure	Heat-treatment
	C	Si	Mn	P	S	Cr	Tensile strength kg/mm^2	Elongation %	Bending		
M-720	2.49	1.05	0.27	0.106	0.096	0.036	42.0	18.4	180	Temper carbon + Ferrite	900°C·2OH→720°C·4OH
M-719	2.47	1.12	0.26	0.092	0.044	0.040	39.0	18.4	180	〃	〃
SN-428	1.48	3.03	0.26	0.126	0.061	0.043	54.0	15.6	180	Nodular graphite + Ferrite	850°C·3H→750°C·10H

Table 10. Chemical composition and mechanical properties.

Mark	Chemical composition %					Mechanical properties			Microstructure	Heat-treatment
	C	Si	Mn	P	S	Tensile strength kg/mm^2	Elongation %	Bending		
M- 67	2.57	0.82	0.26	0.106	0.045	35.6	14.4	150	Temper carbon + Ferrite	900°C·20H—30H→690~720°C·30H—10→650°C·A·C
M-116	2.43	1.06	0.24	0.092	0.044	37.0	16.0	150	〃	〃
SN- 75	1.52	2.52	0.27	0.082	0.043	49.5	13.0	180	Nodular graphite + Ferrite	850°C·2H→750°C·7HF·C
SN- 76	1.47	2.42	0.24	0.108	0.047	50.1	12.5	180	〃	〃
SN-210	1.18	1.77	0.44	0.018	0.006	61.7	5.0	—	Nodular graphite + Ferrite + Pearlite	850°C·2HF·C
SN-309	1.54	1.52	0.41	0.023	0.004	49.4	4.0	—	〃	

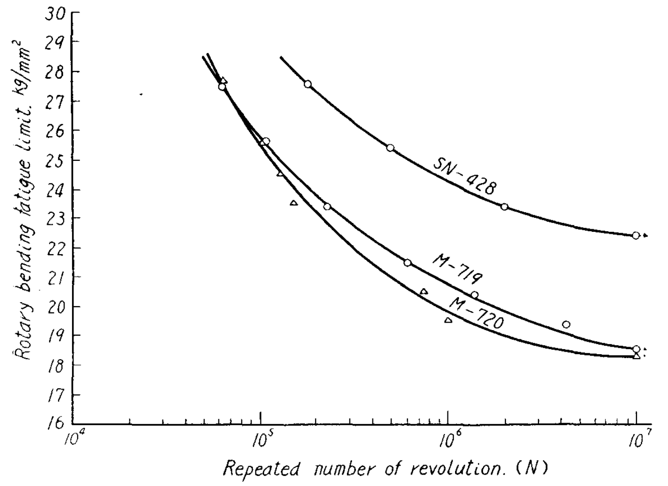
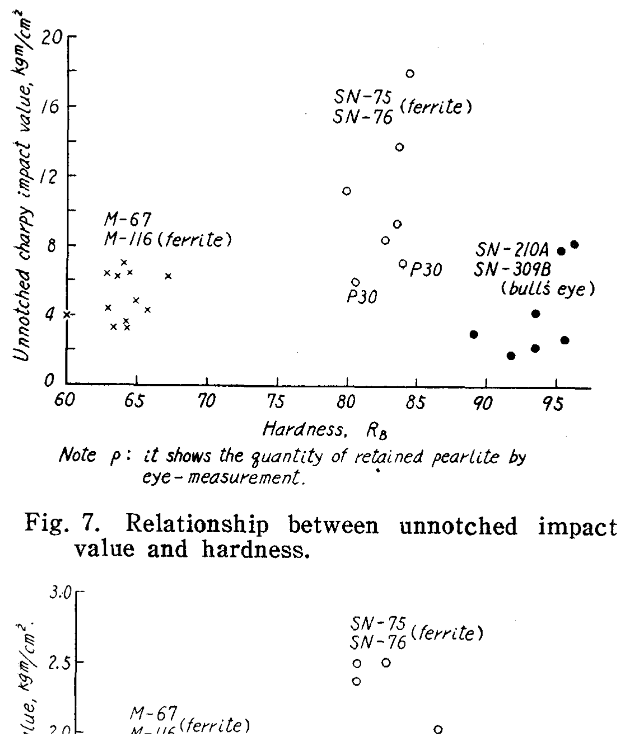


Fig. 6. Fatigue limits of nodular graphite cast steel and malleable cast iron of ferrite matrix.



Note p: it shows the quantity of retained pearlite by eye-measurement.

Fig. 7. Relationship between unnotched impact value and hardness.

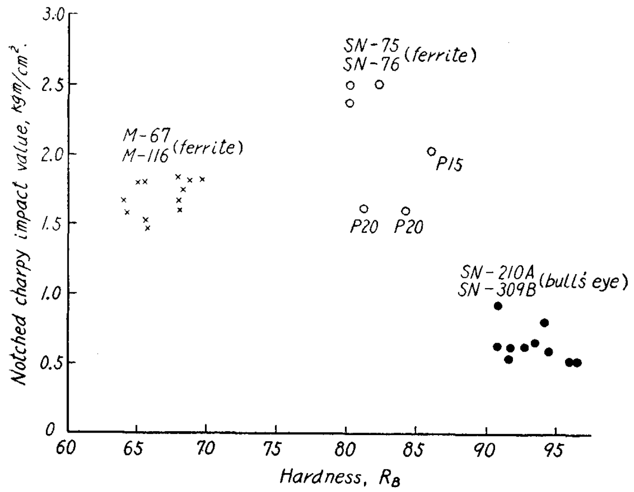


Fig. 8. Relationship between notched impact value and hardness.

the load, the larger the difference was.

The fatigue limit was different according to the state of the test pieces, such as cast or annealed, that is, the influence of the matrix seems to be very large. This is clear from the relation between tensile strength and the fatigue endurance(8). The fatigue limit of ferrite type nodular graphite cast steel was almost similar to that of cast steel, 19~24 kg/mm², and to that of ferrite type DCI, 17~21 kg/mm².

2. Charpy impact test

For the impact test, charpy impact testing machine of 30 kg/m was used. The test-pieces notched and unnotched of JIS No. 3 (10 × 10 × 55.2 × 2 × 1R) were used. The finishing was done by a grinder to the precision degree of 1/100~2/100. In Table 10 the chemical composition, the results of tensile strength, bending and elongation tests, and heat treatment are shown. The relation between the impact value and the hardness is shown in Figs. 7 and 8. Any piece of nodular graphite cast steel (SN) of ferrite type showed superior properties to those of black heart malleable cast iron (M) of ferrite type. Besides, R_B hardness increased due to the high content of the silicon which forms ferrite solid

(8) A. Wittmoser, VDI-Zeits., **93** (1951) 3, 49.
H. Mühlberger, VDI-Zeits., **98** (1956) 24, 1449.

Table 11. Chemical composition and mechanical properties.

Mark	Variety	Chemical composition %						Microstructure	Mechanical properties				
		C	Si	Mn	P	S	Cr		Tensile strength kg/mm^2	Elongation %	Hardness		
											B.H.N	R_C	R_B
O	Ordinary cast iron	3.54	1.79	0.48	0.310	0.098	0.024	C.F.G+P+S	16.9	—	148		79.7
OC	〃	3.43	1.46	0.26	0.032	0.030	trace	E.G+P+F	25.2	—	179	5.0	
SWF-A	Wormy flake graphite cast iron	2.81	1.04	0.38	0.033	0.005	0.010	W.F.G+P	36.0	—	204	14.5	
$M-F_2$	Black heart malleable cast iron	2.37	0.81	0.24	0.024	0.093	0.010	T.C+F	34.2	11.0	94		63.9
$M-F_3$	〃	2.27	1.00	0.24	0.028	0.110	0.010	T.C+F	35.7	10.8	94		63.9
DCI-P	Ductile cast iron	3.58	2.49	0.39	0.001	0.011	0.005	N.G+P	65.0	1.0	240	23.4	
DCI-SP	〃	3.50	2.46	0.39	0.001	0.011	0.035	N.G+S.P	—	—	278	27.8	
DCI-F	〃	3.45	2.46	0.37	0.013	0.007	0.005	N.G+F	45.5	11.0	138		79.2
SN-A	Nodular graphite cast steel	1.58	2.02	0.33	0.073	0.016	trace	N.G+P	61.8	1.0	296	30.5	
SN-SP	〃	1.66	1.66	0.41	0.015	0.006	0.015	N.G+S.P	72.8	2.0	287	29.2	
SN-FO	〃	1.35	2.47	0.38	0.001	0.020	0.029	N.G+F	50.0	11.9	140		82.1

Note C.F.G. : Coarse flake graphite; E.G. : Eutectic graphite; W.F.G. : Wormy flake graphite; T.C. : Temper carbon;
N.G. : Nodular graphite; P : Pearlite; S : Steadite; F ; Ferrite; S.P. : Sorbitic pearlite.

solution.

The impact value of black heart malleable cast iron of ferrite type and that of nodular graphite cast steel of bull's eye type were different in the case of notched pieces, but they were nearly the same or the latter showed somewhat superior value in the case of unnotched pieces.

X. Wear resisting property

The size of the test-piece for Amsler wear test is shown in Fig. 9. Disc pieces of 40 mm in diameter, 10 mm in thickness with a hole of 16 mm in diameter were cut from a bar of green sand mould cast steel of 50 mm in diameter. The rolling test accompanied by sliding was carried out. The rolling velocity of the test pieces was 166 r.p.m. for the upper one and 185 r.p.m. for the lower one. The sliding degree was 10 per cent and the sliding velocity was about 0.04 m/sec. The dry and oil abrasion tests were carried out. The chemical composition, the microstructure and the mechanical properties of the test pieces are shown in Table 11. The values of tensile strength of flake graphite cast iron cut into JIS No.8 C, nodular graphite cast steel, DCI and malleable cast iron of JIS No.4 as cast or heat-treated are shown.

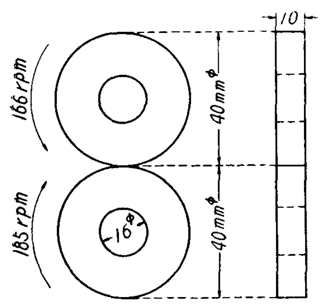


Fig. 9. The size of the test pieces for Amslar testing machine.

(i) Dry abrasion

Fig. 10 shows the results of the abrasion tests

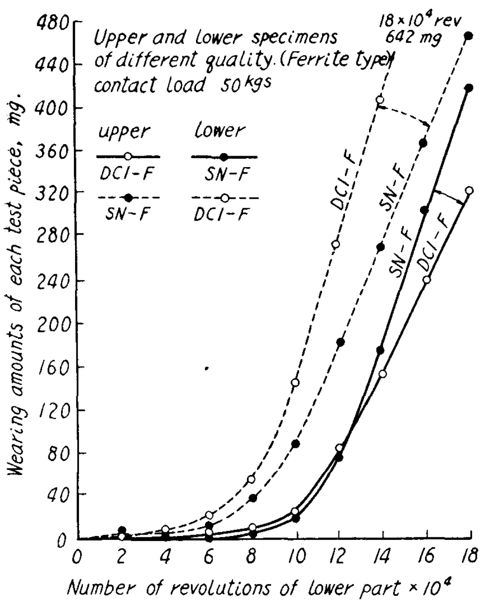


Fig. 10. Amslar type dry abrasion.

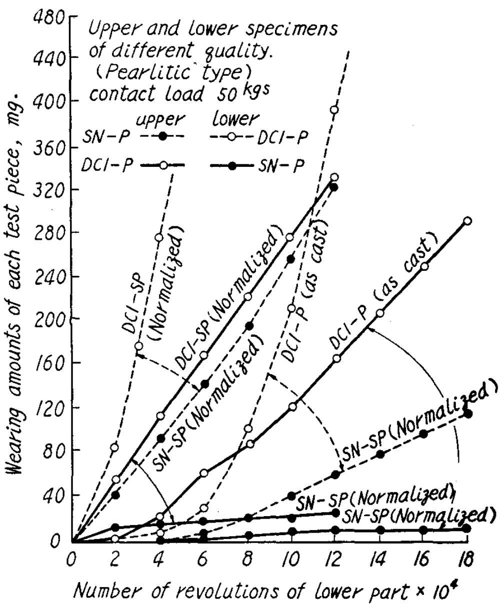


Fig. 11. Amslar type dry abrasion.

with DCI and nodular graphite cast steel of ferrite type, by changing the combination of the upper and lower pieces, under the load of 50 kg. The lower test-piece always showed a little larger value than the upper one in abrasion.

From the results, these two materials seem to have the similar tendency in abrasion.

Fig. 11 shows the results of the abrasion tests by using DCI of pearlite matrix (as cast) for the upper piece, and nodular graphite cast steel of sorbitic pearlite matrix for the lower piece. The abrasion degree of both pieces was very large due to the low hardness of DCI. Further, even when DCI of sorbitic pearlite matrix (by normalizing treatment) was used, it showed higher abrasion degree than the nodular graphite cast steel of sorbitic pearlite matrix, in spite of its higher hardness and higher carbon content than the latter. This fact tells that the nodular graphite cast steel has a good wear resistivity.

(ii) Oil abrasion

Oil abrasion test was carried out by using the upper and lower pieces of the same mater:al. Fig. 12 shows the results of the tests in which ordinary cast iron, wormy flaky graphite high-strength cast iron and nodular graphite cast steel of pearlite matrix were used under the contact load of 100 kg.

The wear resistivity was high in the order of nodular graphite cast steel, high-strength cast iron and ordinary cast iron.

Fig. 13 shows the result of abrasion test in which the same material of ferrite type for upper and lower pieces was used under the load of 150 kg. The nodular graphite cast steel and DCI showed the same tendency in abrasion and far better properties than malleable cast iron.

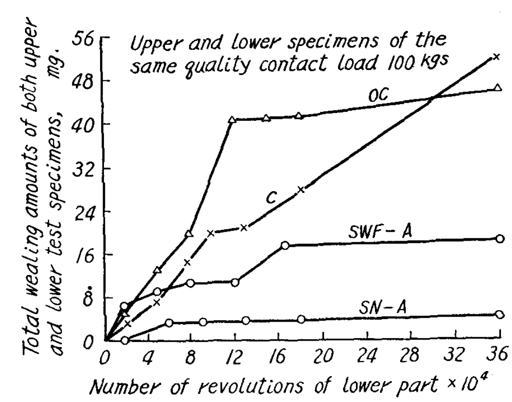


Fig. 12. Amslar type oil abrasion.

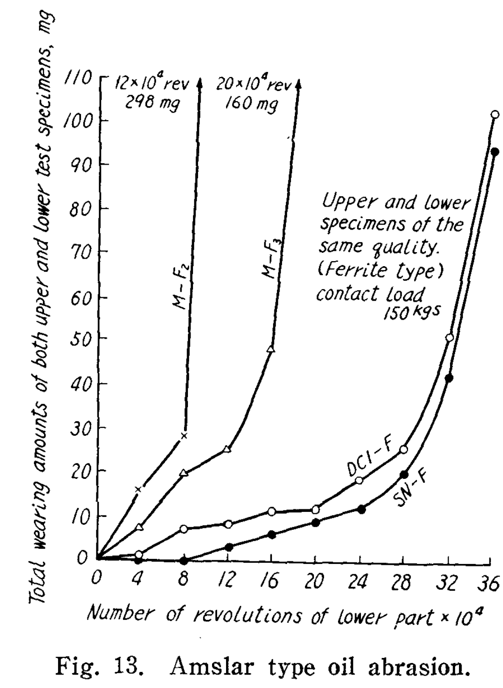


Fig. 13. Amslar type oil abrasion.

Summary

The study of the relation between various properties of cast iron and the oxygen content was systematically done, and the theory of the heredity and the manufacturing method of nodular graphite hyper-eutectoid cast steel was clarified (Fig. 1). Based on this fundamental theory, a nodular graphite hyper-eutectoid cast steel containing less than 1.7 per cent carbon and less than 6.0 per cent silicon was produced, that is, when the reciprocal relation between carbon and silicon contents was chosen between the points on the line E_γ or in the lower areas under the line E_γ in the basic projection

diagram of the Fe-C-Si system shown in Fig. 2, this cast steel was obtained. The various properties of this nodular graphite cast steel were as follows:

(1) The nodular graphite cast steel was not affected by the raw material, and was superior to ductile cast iron, malleable cast iron and ordinary cast steel in mechanical properties, especially in tensile strength, impact value and fatigue limit.

(2) The castability of this cast steel was better than those of ordinary cast steel and DCI, so it is possible to manufacture castings of thin section and complicated shapes.

(3) The impact value of this cast steel of ferrite type in the case of notched piece was 2.0~3.0 $kg \cdot m/cm^2$ and that of black heart malleable cast iron was 1.4~1.8 $kg \cdot m/cm^2$.

The rotary bending fatigue strength of this cast steel was 22~23 kg/cm^2 and that of black heart malleable cast iron was 18~19 kg/cm^2.

(4) Comparing with gray cast iron and malleable cast iron, this cast steel had high permeability, low coercive force and small hysteresis loss, so it can be concluded that this cast steel is very suitable for electric and magnetic material.

(5) From high frequency induction surface hardening tests, it can be said that this cast steel of pearlite and bull's eye types are suitable as the high frequency induction material. Also in the case of ferrite type the surface hardness of Rc 40~50 was obtained.

(6) The wear resistivity of this cast steel of pearlite type was superior to those of flaky graphite high strength cast iron and DCI. In the case of ferrite type its wear resistivity was similar to that of DCI, but superior to that of black heart malleable cast iron.

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