

Welding of Cast Iron and Nodular Graphite Cast Steel. I : Properties of the Heat Affected Zone of Cast Iron

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Welding of Cast Iron and Nodular Graphite Cast Steel. I

Properties of the Heat Affected Zone of Cast Iron*

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Synopsis

Metallographic studies have been made on the structure and properties of the weld heat-affected zone in cast iron by the single-bead tests. The thickness of the ledeburitic layer varies with the melting point of the electrodes. In the martensitic layer, "white" and "dark" martensite were observed by using different electrodes and various welding conditions. It was determined from the isothermal transformation diagrams that these two types of martensite correspond respectively to fast and slow cooling below the M_s point, the critical cooling rate being about 1°C/sec. The amount of retained austenite was about 17 to 27 per cent, showing no appreciable difference between the electrodes. It was pointed out from the calculation that the diffusion of nickel from the deposited metal to the heat-affected zone was negligibly small.

I. Introduction

Cast iron is difficult to weld because it has a high hardenability with thermal shock, a high crack-sensitivity and other undesirable properties for fusion welding. As the welding is of importance for the repair of castings as well as for joining of parts of castings, many investigators have made efforts to obtain sound welds.^{(1)~(12)} However, the low weldability of cast iron is not yet entirely overcome, though the use of the low-temperature welding rods, especially of nickel and nickel-base alloy electrodes has appreciably reduced the difficulties of the welding.

The present report is concerned with studies on the microstructure and me-

* The 995th report of the Research Institute for Iron, Steel and Other Metals. Reported in Japanese in the J. Welding Soc. Japan, (in press).

(1) W. Spraragen and G. E. Claussen, *Weld. J.*, **16** (1937), No. 3, Research Supplement, 2.

(2) W. Spraragen and G. E. Claussen, *ibid.*, No. 6, Research Supplement, 10.

(3) J. M. Diebold, J. A. Blastic and J. A. Griffin, *Trans. Am. Foundrymen's Assoc.*, **54** (1946), 343.

(4) H. Shibata and H. Tamura, *Welding of Cast Irons*, Tokyo, (1955).

(5) E. E. Hucke and H. Udin, *Weld. J.*, **32** (1953), 378-s.

(6) T. E. Kihlgren and H. C. Waugh, *Weld. J.*, **32** (1953), 947.

(7) H. Beyer, *Giesserei*, **44** (1957), 374.

(8) M. Miyoshi, *Kobé-Seiko*, **9** (1959), 179.

(9) R. O. Day, J. S. Snyder and H. V. Inskeep, *Weld. J.*, **36** (1957), 410-s.

(10) W. A. Schumbacker and A. L. Schaeffler, *Weld. J.*, **35** (1956), 91-s.

(11) B. Townshend and E. O. Porter, *Weld. J.*, **38** (1959), 329-s.

(12) I. Onishi and M. Takemasu, The report presented at the Spring Meeting of Japan Welding Soc. (1959).

chanical properties of the heat-affected zone caused by the arc-welding of cast iron. Recently, the utilization of cast iron has been widely extended, not only by the development of nodular cast iron, but also by the improvement of the properties of flake-graphite cast iron. The present work is mainly concerned with flake-graphite cast iron. High strength is now necessary even in the welding of such materials, because the parent metals now have considerably high properties. This is a difference in situation between the earlier studies and the present one.

II. Materials

The cast irons used are tabulated in Table 1. The first group of these materials is ordinary gray cast iron having flake-graphite and relatively low mechanical strength. No tensile test was made for this group, but the tensile

Table 1. Chemical composition and properties of cast iron.

Materials	Chemical analysis					Matrix	Tensile strength kg/mm ²
	C	Si	Mn	P	S		
Ordinary cast iron-1	3.44	1.38	0.58	0.17	0.026	Pearlitic	—
" -2	3.40	2.11	0.67	0.16	0.040	"	—
" -3	3.40	0.92	0.62	0.15	0.018	"	—
Wormy-flake graphite cast iron	2.84	2.57	0.40	0.032	0.096	"	45.8
Nodular graphite cast steel	1.25	2.28	0.25	0.11	0.013	"	75.0

strength is supposed to be 15 to 20 kg/mm². The second group is wormy-flake graphite cast iron, which is a kind of flake-graphite high-strength cast iron, refined in the Héroult furnace by using reducing slag.⁽¹³⁾ The third group is the nodular graphite cast steel, which was used for obtaining the S-curve. No further test was done in the present report. In the next report, the tests and experiments of the welding of nodular graphite cast steel will be reported, when the properties of this material will be explained in detail.

Commercial coated electrodes were used for all tests. The electrodes used, except the D43 type, are summarized in Table 2.

Table 2. Electrodes.

Type	Maker	Coating	Chem. compn. of wire
Cast iron	T	Carbon type	C, 3.31 % ; Si, 3.70 % ; Mn, 0.49 %
Ni	"	"	Ni
Ni-55	"	"	Ni, 55~60
Ni-55	N	"	"

(13) M. Homma, Imono (Castings), 31 (1959), 477.

III. Microstructure of the heat-affected zone

1. Methods

The single-bead method^{(14),(15)} was adopted to obtain typical welds and heat-affected zones, on which the microscopic observation and other tests were performed. On a test plate of 20×75×200 mm, which was made by casting and finished by grinding to remove the surface layer, a weld bead of 10 to 12 cm long was placed by manual welding using the ordinary A.C. welder. The standard welding current and welding speed were respectively 135A and 24 cm/min for 4 mm rods, and in some cases somewhat different conditions were adopted as will be described. The inclination of electrode and other techniques were not varied with the different types of electrodes. The beaded plate was cut normally to the bead to make microscopic observations.

2. Ledeburitic layer

The typical cross-section of a bead is shown in Fig. 1. Two layers, ledeburitic and martensitic, are observed in a heat-affected zone, and the thickness of the former depends upon the kind of electrode. The comparison between the thickness of the ledeburitic layer by a low-carbon steel electrode and that by a nickel electrode is shown in Table 3. When the cast-iron electrode was used, no distinct boundary was observed between the ledeburitic layer and the deposited metal, because the latter also shows ledeburitic structure. The figures in Table 3 are the averaged value of 4 to 6 measurements, and it will be seen that the use of the low-carbon steel electrode produces a thicker

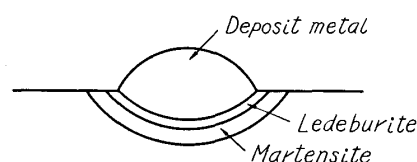


Fig. 1. The structure of heat-affected zone in the single-bead test of cast iron.

Table 3. Averaged thickness of ledeburitic layer. (in mm)

Electrode	Position in the section of bead	
	Center	Near to edge
Ni	0.075	0.048
Low-carbon steel	0.118	0.107

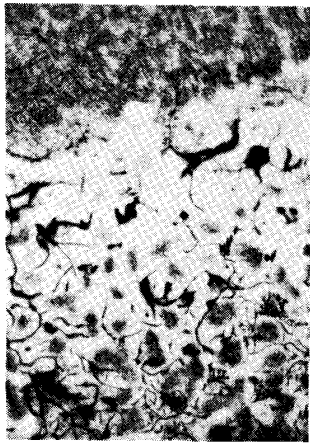
layer of ledeburite than that of the nickel electrode, and that the layer is thicker at the center of the bead than at a position close to the edge.

Several causes will be considered to account for the formation of ledeburite. Of the physical causes the high rate of solidification may be the most effective one. It has also been suggested⁽¹⁾ that the escape of carbon and silicon from the fusion zone, the properties of the flame in gas welding, and the presence of some

(14) A. W. Manlove, *Weld. J.*, **20** (1941), 324-s.

(15) H. Kihara, H. Suzuki and F. Kanatani, *Trans. National Res. Inst. Metals*, **1** (1959), 39.

inclusions have some influence on the formation of ledeburite. Though it is very probable that the contents of carbon and silicon and also of oxygen⁽¹³⁾ have some influence on the formation and decomposition of ledeburite, the major cause may be the high rate of cooling during arc-welding, in which the cooling rate is far higher than in ordinary castings. While the critical cooling rate of precipitation of graphite is about 120°/min even under the most appropriate conditions,⁽¹⁶⁾ the cooling rate in the single-bead welding reaches about 30 to 100°C/sec at the temperature at which the graphitization may most effectively proceed. Thus, the cooling



× 25

Photo. 1. Microphotograph of the heat-affected zone in the single-beaded gray cast iron.

Rod ; 4 mm cast iron.
Welding condition ; 135 A,
24 cm/min.



× 100

Photo. 2. Microphotograph of martensite in heat-affected zone.

Rod ; 4 mm cast iron.
Welding condition ; 135 A,
24 cm/min.



× 100

Photo. 3. Microphotograph of martensite in heat-affected zone.

Rod ; 4 mm nickel.
Welding condition ; 135 A,
24 cm/min.



× 100

Photo. 4. Microphotograph of martensite in heat-affected zone.

Rod ; 4 mm low-carbon steel.
Welding condition ; 135 A,
24 cm/min.



× 100

Photo. 5. Microphotograph of martensite in heat-affected zone.

Rod ; 5 mm cast iron.
Welding condition ; 200 A,
24 cm/min.



× 100

Photo. 6. Microphotograph of martensite in heat-affected zone.

Rod ; 4 mm cast iron.
Welding condition ; 135 A,
12 cm/min.

(16) I. Suzuki, Mitsubishi-Denki, 30 (1956), No. 6, 1.

rate in welding is about 10 to 50 times higher than the critical cooling rate of graphitization.

The difference in thickness of the ledeburitic layer may relate to the melting points of the welding rods. As shown in Table 3, the nickel electrode yields a thinner layer than the low-carbon steel electrode. This is probably due to the lower melting point of the nickel electrode than the low-carbon steel electrode.

3. Martensitic layer

Appreciable differences in the martensitic layer were observed between those formed by the various electrodes as shown in Photos. 1 to 6. Photo. 1 shows with low magnification the martensitic layer formed by the cast-iron electrode. The cavities around the graphite flakes are formed during the polishing procedure owing to brittleness of martensite. Photo. 2 also shows martensite by the cast-iron electrode, showing "white" martensite. Photos. 3 and 4 show respectively those by nickel electrode and by low-carbon steel electrode, showing "dark" martensite. Photo. 5 is of cast-iron electrode using a higher welding current, and shows dark martensite. Photo. 6 is also of cast-iron electrode with a low welding speed, showing the dark martensite and primary cementite accompanied by primary troostite.

It is well known that the martensite is darkened by short-time tempering at 100°C to 300°C owing to its partial decomposition to ϵ -carbide. The dark martensite appearing in Photos. 3 to 6 may be similar, which is formed by the relatively slow rate of cooling below the M_s point. This was confirmed from the observation of the isothermal transformation, as will be described in the following section.

IV. The determination of S-curves

The S-curves were determined to obtain information on the weldability of these materials. There are only a few reports^{(17),(18)} concerning S-curves of cast iron, most of which are of alloy cast iron.

The determinations were made by adopting 1050°C and 5 min (for ordinary C.I. and N.G. cast steel) or 2 min (for wormy-flake G.C.I.) as the austenitization temperature and time, respectively, which gave sufficiently reproducible results. After quenching and holding isothermally in a salt bath or oil bath, the degree of transition was estimated by microscopic observation. The M_s point was determined by the Greninger-Troiano's method.

The S-curves thus obtained are shown in Figs. 2, 3 and 4. Though these curves are similar to one another, some minor differences are observed about the positions of the B_s and B_f lines. In the lower bainite region, wormy-flake graphite cast iron shows the shortest incubation period, and nodular graphite cast steel the longest period, while the latter shows a shorter B_f period than others.

(17) A. DeSy and J. van Eeghen, *Giesserei*, **44** (1957), 8, 189.

(18) T. Ototani, Y. Tokunaga and N. Takahashi, *Imono (Castings)*, **31** (1959), 84.

The broken lines which are drawn below the M_s point indicate the boundary of the white and the dark martensites. These lines may have a somewhat broad

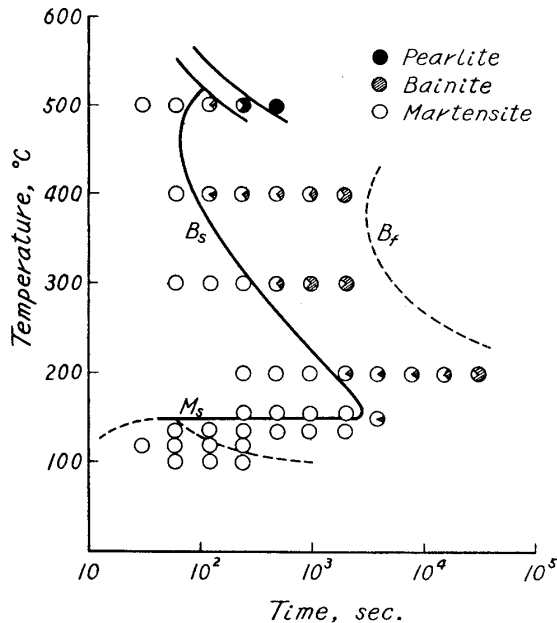


Fig. 2. S-curve of wormy-flake graphite cast iron.

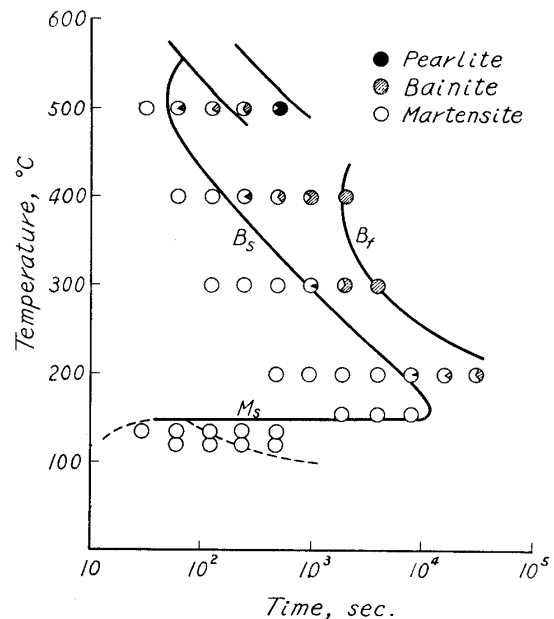


Fig. 3. S-curve of nodular graphite cast steel.

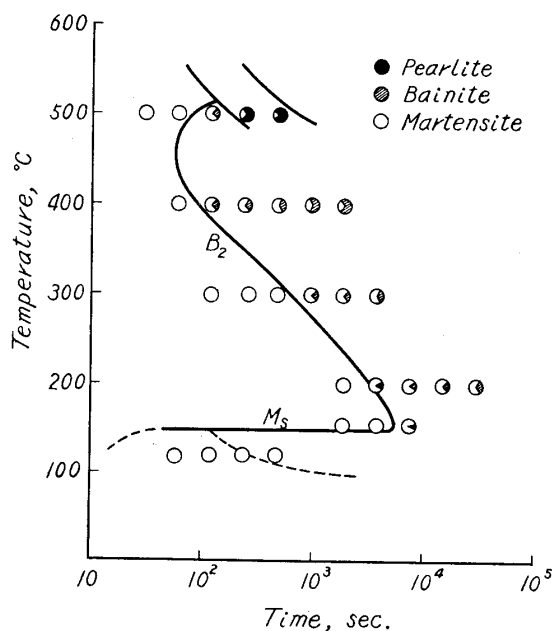


Fig. 4. S-curve of ordinary gray cast iron.

range, because the darkening of martensite is not a sudden change, but a gradual process. In Photos. 7a to 7c, the darkening of the martensite is illustrated.

The dark martensite may appear when the rate of cooling is sufficiently low at a temperature below the M_s point. Though the critical cooling rate resulting in the dark martensite can not be directly determined from the isothermal transformation curve, a rough estimation can be made providing the additive rule⁽¹⁹⁾ is obeyed. The critical cooling rate thus calculated⁽²⁰⁾ was of the order of 1°C/sec.

V. Hardness of the heat-affected zone

The hardness of the martensitic layer was practically independent of the type of electrode or of the darkening of the martensite. In Fig. 5 a comparison of the hardness of the martensitic layers formed by a cast iron electrode and by a nickel

(19) J. H. Cahn, *Acta Met.*, 4 (1956), 572.

(20) M. Homma, T. Wada and K. Yamaya, *J. Weld. Soc. Japan*, (in press).

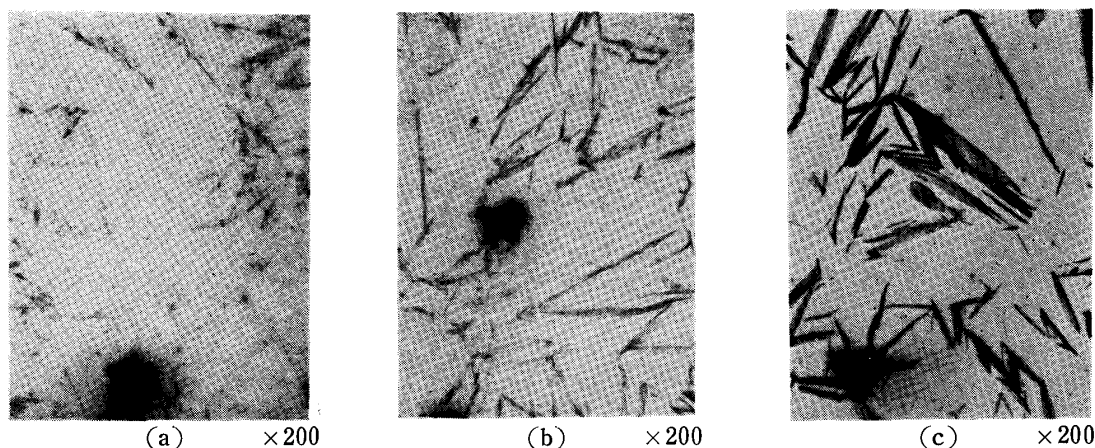


Photo. 7. Martensite in isothermal transformation of nodular graphite cast steel.

- (a) Transformation at 135°, 30 sec, showing white martensite.
- (b) Transformation at 135°, 1 min, showing slightly darkened martensite.
- (c) Transformation at 135°, 4 min, showing dark martensite.

electrode is shown. The test plate of this experiment was made of ordinary cast iron, and the microvickers hardness was measured with a loading of 200 g, avoiding to fall into the graphite cavities. Thus, practically no difference was observed between these two electrodes, either in the maximum hardness or in the width of hardening zone.

The thickness of the heat-affected zone has been considered, so far, to be dependent on the type of electrode. Though this is correct for the ledeburitic layer, the thickness of martensitic layer is not varied with the electrode, as far as a fixed welding condition is used. The difference in the thickness of the martensitic layer may mainly be attributed to the difference in the welding current, voltage and speed.

The change in the hardness of the heat-affected zone by annealing was examined, and the results obtained were in agreement with those deduced from the tempering of martensite and the decomposition of ledeburite. Fig. 6 shows the change in hardness of the martensitic layer formed in ordinary cast-iron plate by using a cast-iron electrode and by annealing at 300°C and 400°C for 5 to 20 min. Thus, it is shown that the decrease in the hardness is relatively small under such annealing conditions, which is in agreement with the results obtained by tempering martensite.⁽²¹⁾

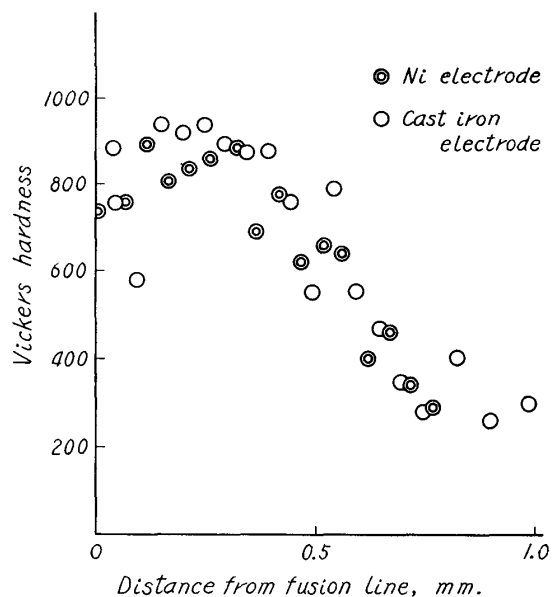


Fig. 5. Hardness in the martensitic layer of gray cast iron.

(21) B. S. Lement, B. L. Averbach and M. Cohen, *Trans. A.S.M.*, 46 (1954), 851.

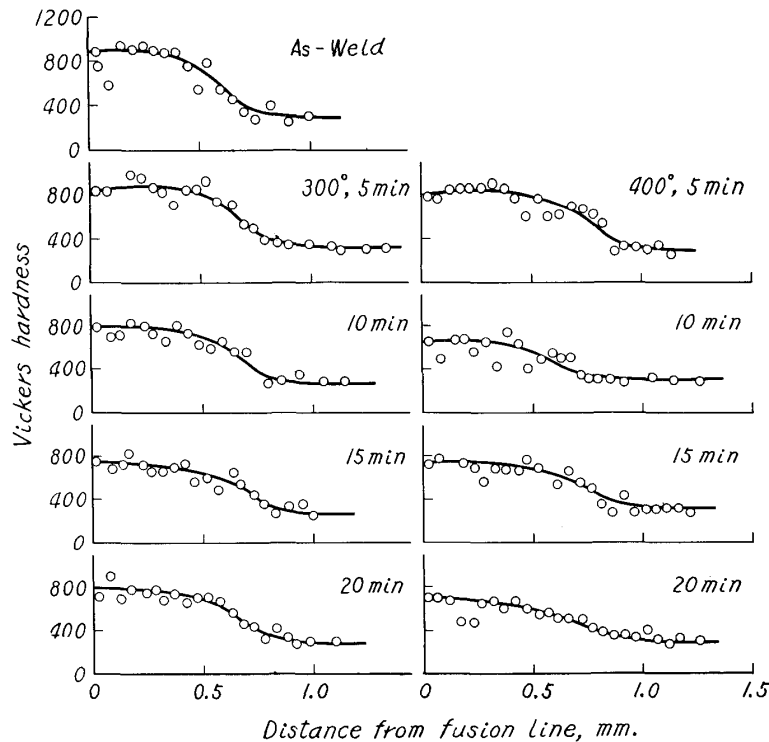


Fig. 6. Change in hardness of martensitic layer by annealing.
(Gray cast iron)

VI. Retained austenite

Because of the slow cooling rate below the M_s point it may be probable that the amount of retained austenite is increased.⁽²²⁾ Therefore, its amount was determined by the point-counting method.⁽²³⁾

Small pieces were cut out from the heat-affected zone, and after a short-time tempering at 300°C for 10 sec in order to darken the martensite, microphotographs were taken, for which the point-counting was done to determine the retained austenite. The results are shown in Table 4.

There are a few cases of local increase in the amount of retained austenite,

Table 4. Retained austenite in martensitic heat-affected zone.

Rod Obs. No.	Cast iron 135A, 24 cm/min	Cast iron 135A, 12 cm/min	Low-C steel 135A, 24 cm/min	Ni 135A, 24 cm/min
1	31.0%	13.9	19.3	23.5
2	18.2	13.9	53.2	20.8
3	14.6	17.1	26.3	17.1
4	30.5	25.3	37.1	33.7
5	35.3	15.0	13.4	23.5
6	20.3	17.7	14.5	25.2
Average	25.0	17.2	27.3	24.0

(22) Y. Imai and M. Izumiyama, *J. Japan Inst. Metals*, **21** (1957), 437.

(23) R. T. Howard and M. Cohen, *Met. Techn.*, **14** (1947), T. P. 2215.

reaching about 40 per cent or more. The averaged values, however, are about 17 to 27 per cent, which are not of a extremely high value. 1.12 per cent C steel quenched at room temperature has retained austenite of about 20 per cent⁽²⁴⁾, and it is quite reasonable that the percentage of carbon reaches 1.2 to 1.3 per cent in the matrix of the heat-affected zone. Though the averaged values are thus reasonable, the local increase in retained austenite may have some influence on the properties of the heat-affected zone. The lack of uniformity in the formation of martensite may result in nonuniform stresses, which are effective for crack-formation.

As shown in Table 4, the type of electrode has practically no influence on the amount of retained austenite. The slow speed of welding, on the other hand, yields a remarkable decrease in retained austenite, as shown in column 2 in Table 4. The cooling rate of this specimen seems to be lower than those of the others, and therefore, the degree of super-saturation of carbon in the matrix may also be lower than the others, owing to the lower rate of cooling across the Ac_m line. The microstructure revealing the existence of boundary cementite accompanied by troostite may also support this interpretation.

VII. Diffusion of nickel and carbon in the heat-affected zone

The diffusion of nickel and carbon between the weld metal and the heat-affected zone will be discussed. There is an opinion that nickel may diffuse into the heat-affected zone from the weld metal, and the superior properties of nickel or nickel-55 may more or less be attributed to it. A question may arise, however, whether nickel can actually diffuse into the heat-affected zone, or not.

Now, an approximate calculation will be made by using the diffusion coefficients of nickel and carbon in iron. It must be taken into consideration that the welding process is not isothermal, but its temperature is highly time-dependent.

Generally, in isothermal diffusion, the concentration c of a diffusing species is given by the solution of Fick's equation with the infinite boundary condition⁽²⁵⁾ as

$$c = \frac{c_0}{2} \{1 - \operatorname{erf}(x/2\sqrt{Dt})\}. \quad (1)$$

In the present case, diffusion coefficient D is time-dependent. The approximate treatment is done by defining "averaged diffusion coefficient" \bar{D} by

$$\bar{D} = \frac{1}{t} \int_0^t D dt, \quad (2)$$

and using \bar{D} instead D in Eq. (1). D is given by

$$D = D_0 \exp - \frac{E}{RT}, \quad (3)$$

so Eq. (2) becomes

(24) R. T. Howard and M. Cohen, *Trans. AIME*, **176** (1948), 384.

(25) W. Jost, *Diffusion in Solids, Liquids, Gases*, Academic Press, N. Y. (1952).

$$\bar{D} = \frac{D_0}{t} \int_0^t \left(\exp - \frac{E}{RT} \right) dt. \quad (4)$$

The weld thermal cycle was determined by Suzuki et al.⁽¹⁵⁾ for single-bead welding under various conditions. In the present calculation, their results of beading at 170A on a 20 mm plate were employed. The diffusion coefficients of nickel and carbon in austenite used here are those obtained by the measurement of Wells and Mehl.^{(26), (27)}

The penetration curves of nickel and carbon during the single-beading thermal cycle were obtained as shown in Fig. 7.

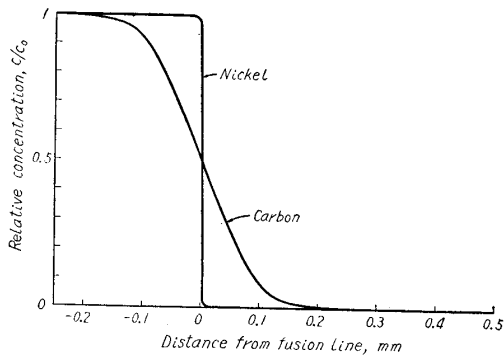


Fig. 7. Diffusion of nickel and of carbon in heat-affected zone by the weld thermal cycle, calculated from diffusion coefficients in austenite.

It is observed that carbon migrates into or from the heat-affected zone with a diffusing layer of about 0.2 mm, whereas nickel is very hard to diffuse, yielding a diffusing layer of only about 10^{-2} mm. Though this is a rough estimation, the diffusion of nickel into the heat-affected zone is considered to be very difficult. It can thus hardly be expected that nickel has any influence of the diffusion on the properties of the heat-affected zone. Carbon yields a relatively wide

diffusing layer, extending over about one fifth of the heat-affected zone. But actually, the presence of the ledeburitic layer may prevent the diffusion of carbon, and graphite may supply carbon compensating its decrease in the matrix. So the actual decarburization in the matrix is probably very much lower than that shown in Fig. 7.

VIII. Discussions and conclusions

The heat-affected zone of arc-welded cast iron is composed of two layers, ledeburitic and martensitic. As described above, the thickness of the ledeburite layer relates to the melting point of the welding rod. Except the cast iron electrode, in which the ledeburitic layer is not distinguishable, either a nickel or a low-carbon steel electrode has a higher melting point than the parent metals. So the fusion of the parent metal may proceed even after the weld metal has solidified. Thus, the fusion layer, which yields the ledeburitic layer by solidification, becomes wide with melting point of electrode.

The thickness of the martensitic layer, on the other hand, is influenced very little by the welding rods, but depends mainly on the welding conditions such as the welding current and welding speed. So far it was often considered that the heat-affected zone of cast iron remarkably depended on the type of electrode.

(26) C. Wells and R. F. Mehl, *Met. Techn.* **7** (1940), T. P. 1180.

(27) C. Wells and R. F. Mehl, *Trans. AIME*, **145** (1941), 329.

But this may be due mainly to the difference in the optimum current for each electrode and not to the different chemical effects of electrodes.

Microscopic observations of martensite showed a difference between the cast iron and other electrodes. This is probably due to minor differences in the cooling rates below the M_s points. The effect of decarburization is hardly probable, because the amount of retained austenite practically does not vary with the different kinds of electrodes. According to the calculation from the diffusion coefficient, however, it is shown that carbon can diffuse appreciably into or from the heat-affected zone. In practical welding, in which the cooling rate is usually lower than that of single-beading, it may be probable that the decarburization occurs appreciably in the heat-affected zone.

The superiority of nickel and nickel-base alloy electrodes is probably due to the high ductility of the weld metal as well as to the low melting-point of the electrodes. The latter factor yields a thinner ledeburitic layer than the steel electrodes. The martensitic layer, however, is practically not different from those of other electrodes, if the same welding condition is used.

The weld crack, especially under-bead crack of cast iron may be closely related to the stress of the formation of martensite. If the formation of martensite is not uniform, nonuniform stresses may arise in the heat-affected zone, which would stimulate the crack-formation. The uniformity of formation of martensite may be influenced by the local super-saturation of carbon in the matrix. So the nonuniformity may be prevented by avoiding over-heating and by slow cooling at A_{cm} temperature.

Summary

Metallographic studies were made on the structure and properties of the weld heat-affected zone in cast irons. The results are summarized as follows:

(1) The heat-affected zone of cast iron is composed of two layers, ledeburitic and martensitic, the former varying in its thickness with the melting point of the electrodes.

(2) In the martensitic layer, "white" or "dark" martensite was observed by using various electrodes and welding conditions. These two types of martensite corresponded to fast and slow cooling rates below M_s point. The thickness of the martensitic layer is practically independent of the kind of electrode as far as the welding condition is not varied.

(3) The isothermal transformation curves were determined for ordinary cast iron, wormy-flake graphite cast iron, and nodular graphite cast steel. The isothermal darkening of martensite was also observed.

(4) The amount of retained austenite in the heat-affected zone was about 17 to 27 per cent, indicating no appreciable difference between the electrodes used.

(5) It was pointed out by calculation that the diffusion of nickel from the deposit metal to the heat-affected zone was negligible.