In heat 11, graphitization in the A_{c1}–A_{c3} region lagged that in the unaffected parent metal.

In heat 12, graphite in the A_{c1}–A_{c3} region was quite similar to that in the unaffected parent metal.

It appears that generalizations cannot be made regarding most aspects of the graphitization process in the A_{c1}–A_{c3} regions of the test materials. However, one observation can be made. Just as in the unaffected parent metal, there was a tendency for those heats high in N and low in Al to have the longer incubation periods while the low-N high-Al heats tended to have the shorter incubation periods. Also, the preponderance of evidence supported the thesis that the graphitization process in the A_{c1}–A_{c3} region takes place by a nucleation and growth mechanism.

Conclusions

It is believed that the following tentative conclusions are justified:

1 High total aluminum content, in the presence of minimum amounts of nitrogen, promoted susceptibility toward graphitization.

2 Nitrogen content, substantially in excess of the total aluminum content, promoted resistance toward graphitization. This was brought about by extension of the incubation period in the graphitization process. In two cases, no graphitization occurred even after 8000 hr on test. Perhaps it could be said that, in these instances, the incubation period exceeded 8000 hr.

3 Additions of $^1/_4$ per cent chromium appeared to promote graphitization, even though chromium in amounts exceeding $^1/_2$ per cent renders steel very resistant to graphitization. The effect of the $^1/_4$ per cent chromium addition, however, was not equivalent to that produced by the high-aluminum additions, and the process had an incubation period when chromium was present.

4 Normalizing at 1700 F prior to the graphitization test tended to increase the incubation period in the graphitization process, except when Al was very high and N was very low. Under the latter conditions, the normalizing treatment was ineffective.

The effect of heat-treatment was not discernible in the weld-heat-affected zones of the test materials, probably because the weld bead had been laid after the heat-treating operation.

5 From the behavior of heats 9, 10, 11, and 12, it was speculated that some of the other elements besides Al, N, and Cr might influence the graphitization process. For example, sulphur might promote it, while manganese might tend to retard it.

6 The graphitization process generally took place by means of a nucleation and growth mechanism both in the A_{c1}–A_{c3} region of the weld-heat-affected zone of the test materials and in the unaffected parent metal. This mechanism usually seemed to involve a time rate of nucleation.

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Discussion

Floyd Brown.[5] The effects of third elements on the graphitization of carbide is of particular importance in the manufacture of the various cast irons. It is always interesting to compare the results of investigations on graphitization in steel, which has been actively studied for less than two decades, with the voluminous literature on graphitization in cast iron reaching back to the turn of the century. A study of this literature suggests that only a very few elements are inherent graphitizers, such as copper and nickel (and perhaps a few of the noble metals), and that most elements act as if they are graphitizers because they are, in fact, scavengers of other elements which are strong carbide stabilizers. The following are observations on cast irons related to the subject paper:

1 Wüst observed that in small quantities aluminum in cast iron increased the tendency for carbon to exist as graphite rather than as carbide, although in larger quantities the effect reversed and aluminum appeared to behave as an intrinsic stabilizer of carbide.[6]

2 Nitrogen has been shown to stabilize graphitization in various cast-iron types, an effect which is counteracted by the addition of aluminum.[7]

3 The behavior which the authors found in steels with chromium contents of about $^1/_4$ per cent is reflected in somewhat similar behavior in cast iron.[8]

4 Both manganese and sulphur are known to be strong carbide stabilizers, and a large segment of the malleable-iron industry hinges in fact upon the tendency of high manganese to stabilize the eutectoid carbide to yield a pearlitic malleable iron, while the remainder of the industry carefully balances the sulphur against the manganese to promote the graphitization of this eutectoid carbide. (The optimum manganese/sulphur ratios for these two purposes were determined with care in the laboratory by Rehder.[9])

5 The coalescence of graphite nodules, which as the authors recognized may have occurred in some instances in steels, has been rather convincingly documented in malleable cast irons.[10]

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[5] Research Associate Professor of Metallurgy, North Carolina State College, Raleigh, N. C.

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A. B. Wilder.[11] The authors have presented information of a fundamental nature on the graphitization of steel. They have referred to our work on the influence of nitrogen in carbon steel and on graphitization after the steel had been exposed for 10,000 hr at elevated temperatures. We have observed recently that carbon steels not killed with aluminum and containing about 0.015 per cent nitrogen did not graphitize after 34,000 hr exposure at 900 F and 1050 F. Similar steels with 0.005 per cent nitrogen graphitized.

The authors observed that $^1/_4$ per cent chromium appeared to promote graphitization. We believe steel should contain about 1 per cent chromium and then graphitization will be avoided. Although some electric-furnace steels contain about 0.015 per cent nitrogen, which inhibits graphitization, there have been indications that chromium may combine with nitrogen and therefore remove the effectiveness of nitrogen. Under these conditions the effectiveness of chromium as an inhibitor of graphitization would be retarded, and this may explain why small amounts of chromium appear to promote graphitization.

AISI C-1118 steel with 0.16% C, 1.65% Mn, 0.121% S, and 0.047% Al, and AISI C-1137 steel with 0.37% C, 1.51% Mn, 0.129% S, and 0.023% Al were exposed for 34,000 hr at 900 F and 1050 F. Graphitization was only observed in C-1137 steel. The presence of sulphur and possibly manganese were responsible for the absence of graphitization in the C-1118 steel. Both steels contained an appreciable amount of aluminum.

[11] Chief Metallurgist, National Tube Division, U. S. Steel Corporation, Pittsburgh, Pa.

Authors' Closure

The authors wish to express their appreciation to Professor Brown and Dr. Wilder for their interesting and valuable discussions. The authors are particularly gratified that additional information was bought out which tends to support their observations regarding the influence of small amounts of chromium.