tention that "abnormal" structure by this criterion is an index of graphitization susceptibility in aluminum-treated carbon-molybdenum steels. This rule, however, does not necessarily apply to the steels having chromium additions. Study of microstructures indicates that the particular kind of electric-furnace process, all other factors being equal, is a minor influence as regards graphitization susceptibility.

One generalization which seems to apply with regard to the tests under discussion as well as much other observation, is that the inception of spheroidization agglomeration or coalescence of the carbide precedes its breakdown to graphite. A number of examples have been observed where in a single microfield, one spheroidized-carbide area will show graphite nodules, whereas an adjacent lamellar-carbide area will show no signs of graphite. Where chromium or other alloying ingredients prove effective in preventing graphitization under a certain condition of thermal history, the inhibition seems to be associated with resistance to spheroidization of the carbide. The susceptibility of aluminum-treated steel to graphitization seems to be associated with an accelerated tendency toward spheroidization.

In previous reports by the Joint A.S.T.M.-A.S.M.E. Committee, it has been apparent that strong aluminum treatment of steels led to easy spheroidization and consequent lack of creep resistance.

Proposals have been made to the effect that graphitization at the margin of the heat-affected zone or "contact zone" might be forestalled, or at least reduced to an impotent nature by a grain-refining normalizing heat-treatment subsequent to the welding operation. That such a treatment may not be effective in the case of a susceptible cast steel is evidenced by the micrographs, Fig. 7, comparing one of the weld-bead specimens normalized after deposition. It is seen that "contact zone" graphite has not been inhibited in this specimen. The transformation resulting from welding in the heat-affected zone seems to have some persistent effect, although it does appear that the zone of segregated graphite is somewhat broader, diffuses, and perhaps requires longer aging to detect. Studies upon more specimens normalized after welding are needed to clarify the effect.

CHROMIUM IN CAST STEELS

In so far as the cast-steel studies have progressed (3000 to 5000 hr of aging), no definite evidence of graphitization has become apparent in any of the samples containing chromium in the range of 0.43 to 0.70 per cent as witnessed by Fig. 8, where relatively spheroidization-resistant carbides are well defined. It should be noted that the lowest chromium content is 0.43 and that the time periods involved are as yet relatively short and inconclusive.

It may eventually be determined that resistance to spheroidization is a necessary and perhaps sufficient condition to prevent graphitization over an expected service period.

Specimens of a number of the cast steels upon which the graphitization studies are being made are aging for the eventual purpose of making creep-strength studies on structures representing various stages of carbide deterioration. It has become quite apparent that graphitization has occurred in some of the coupons being aged for creep tests after advanced spheroidization of the carbide had developed. In the case of carbon-molybdenum steel with 2 lb per ton of aluminum addition, well-developed graphite is apparent after about 4000 hr of aging at 1025 F. The coupons containing 0.50 per cent chromium have shown no definite evidence of graphite after 5000 hr of aging. The committee has decided to continue the aging of all coupons for creep tests up to at least 10,000 hr before considering the starting of creep-rate determinations upon any of them.

Discussion

I. A. Rohrig.[3] This report shows that under suitable conditions graphitization may readily occur in cast as well as in wrought carbon-molybdenum steels. The observation of an apparent "persistent effect" resulting in segregated graphite in the heat-affected area of a weld even after normalizing is of particular significance because normalizing has appeared to be the most effective postwelding treatment for preventing segregated graphite. With respect to the normalizing of welds, the results of laboratory graphitization tests conducted on normalized welded samples by The Detroit Edison Company may be of interest.

A sample of high-aluminum carbon-molybdenum pipe mate-

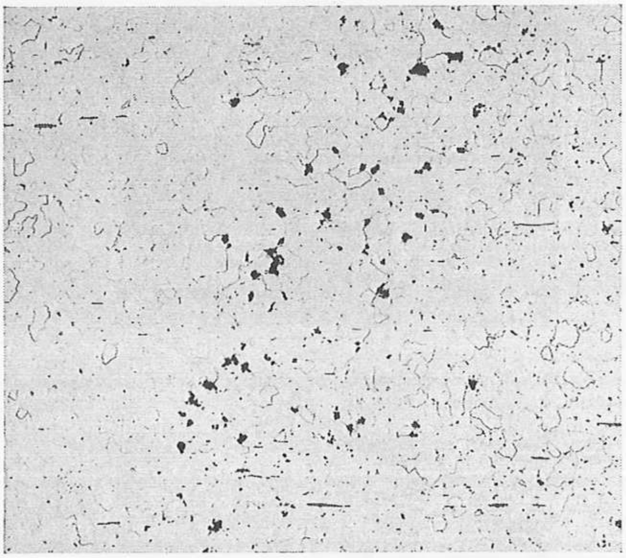

Fig. 9 Segregated Graphite in the Heat-Affected Area of "As-Welded" Carbon-Molybdenum Sample After 10,300 Hr of Laboratory Test Heating

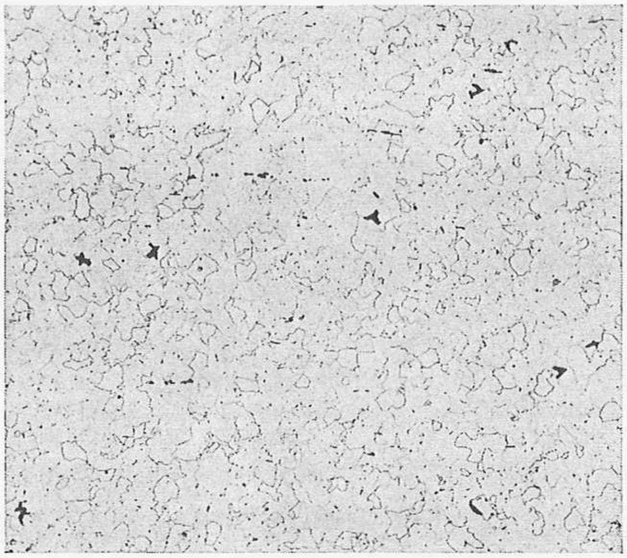

Fig. 10 Random Graphite in Former Heat-Affected Area of a Normalized Weld in Carbon-Molybdenum Sample That Was Laboratory-Heated for 10,300 Hr After Normalizing

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[3] Research Department, The Detroit Edison Company, Detroit, Mich.

rial was welded to low-aluminum material and then normalized by heating for 1 hr at 1725 F, followed by air-cooling. To promote graphitization, "as-welded" as well as "normalized" samples were heated at temperatures varied between 1000 and 1060 F for 3300 hr, and then at temperatures varied between 900 and 1150 F for an additional 7000 hr. After a total time of 10,300 hr of test heating, the as-welded samples showed a distinct segregation of nodular graphite in the heat-affected area whereas the normalized samples showed only random graphitization. Segregated graphite in the heat-affected area of as-welded high-aluminum material is shown in Fig. 9 of this discussion. Random graphitization at the former heat-affected area of the sample that was normalized after welding is shown in Fig. 10. Similar results were found in the low-aluminum material with the exception that considerably less graphite was present.

These results indicated that the normalizing treatment of 1 hr at 1725 F had been fully effective in removing the nucleation effect resulting from the heat of welding. Kerr and Eberle[4] have also reported on the apparent beneficial effect of normalizing after welding as a means of preventing the formation of segregated graphite. The results obtained from test prompt the suggestion therefore that the normalizing treatment used by the author, and which is not stated in the paper, may not have been fully effective in reconstituting and homogenizing the structure of the heat-affected area in his sample.

The author's suggestion that resistance to spheroidization may be a necessary and perhaps sufficient condition to prevent graphitization is probably based upon the hypothesis that spheroidization is the first stage of graphitization. Referring again to the work of Kerr and Eberle,[4] it is noted that they have reported on a number of cases in which steels that had spheroidized were found to be resistant to graphitization. Although spheroidization and graphitization may be parallel phenomena in steel at high temperature, it does not necessarily follow that spheroidization is the first stage of graphitization. In this association it might be pointed out that although the photomicrographs presented in Fig. 6 of the paper, are for the apparent purpose of showing the graphitization susceptibility of the aluminum-treated sample in contrast with the graphitization resistance of the sample having no aluminum addition, the two samples appear to be about equally spheroidized.

AUTHOR'S CLOSURE

Mr. Rohrig's evidence that a sample of high-aluminum carbon-molybdenum pipe material, welded and normalized at 1725 F showed only random graphitization, is in interesting contrast to that on the carbon-molybdenum cast steels studied in the Project No. 29 investigation. Of seven different heats of carbon-molybdenum steel with 2 lb of aluminum addition per ton and normalized at 1650 F for one hour after welding by the various contributors of the specimens, all specimens showed a development of graphite after 5,000 hours of aging at 1025 F, of which the "contact" zone photomicrographs of Fig. 7 are typical. Since the presentation of the report in question, these aging tests have progressed far enough to show that upon 10,000 hours, the average degree of contact zone graphitization for the seven heats of steel normalized after welding is about the average degree which was obtained for a group of six similar heats of steel stress-relieved only after welding upon 4000 hours of aging. This degree of deterioration represents about one third of the carbon transformed to graphite. While normalizing has served to retard the development of graphite at the contact zone, it by no means promises to be a satisfactory measure of control for the carbon-molybdenum cast steels.

Mr. Rohrig questions the observation that spheroidization of carbide is a prelude to graphitization and supports his objection by pointing out that certain samples reported upon showed spheroidization but no graphitization. However, since the report was presented, examinations after 10,000 hours of aging at 1025 F have revealed further spheroidization and graphitization in a number of samples where it had not been found after 5000 hours, including those containing one half of one per cent of chromium, thus indicating that the development of graphite in sequence to spheroidization may be an eventual effect to be always considered relative to aging time, temperature stress, and the composition of the steel.

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[4] Graphitization of Low-Carbon and Low Carbon-Molybdenum Steels" by H. J. Kerr and F. Eberle, A.S.M.E. pamphlet "Graphitization of Steel Piping," included in Trans. A.S.M.E., vol. 67, 1945.