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Mechanical Properties and Structure of Electron Beam Welds in Alloy Fe-0.2%C-12%Cr-1%Mo

EB welded joints in Fe-0.2%C-12%Cr-1%Mo provide notch impact properties that are superior to those of submerged arc welded joints in the same alloy

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ABSTRACT. Electron beam welds were made to join 21 mm (0.83 in.) thick Fe-0.2%C-12%Cr-1%Mo alloy plates. After tempering at 740°C (1364°F) for 2 hours, the welds were investigated by transverse weld Charpy V-notch impact tests at temperatures up to 550°C (1022°F) and also by notched transverse weld and smooth transverse weld tensile tests at room temperature and 550°C (1022°F). Impact tests were also carried out after a subsequent aging treatment at 550°C (1022°F) for 5000 hours. For comparison, all-base-metal specimens were tested in the same way.

EB welds in both the as-welded condition and the tempered condition were investigated using light microscopy and microhardness traverses across the weld. Furthermore, a microprobe line scan across the weld was carried out for the tempered condition.

Impact strength properties of the EB welded joints were remarkably good compared to Charpy V-notch data for welds produced by submerged arc welding. The impact strength of the EB welded joints also exceeded that of the base metal in the temperature range considered, *i.e.*, −60 to 550°C (−76 to 1022°F). This still holds in the temperature range of −60 to 80°C (−76 to 176°F) after subsequent aging for 5000 hours (h) at 550°C (1022°F), whereas at 550°C (1022°F) the impact strength data are virtually equal.

Light optical investigations showed no discontinuites in the EB welded joint. Macrosegregation of chromium and molybdenum across the EB weld could not be observed.

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Introduction

Modified 12%Cr steels are used for high pressure high temperature components in power plants and in the chemical industry (Ref. 1). The alloy Fe-0.2%C-12%Cr-1%Mo is especially used for high pressure vessels and piping because of its high temperature and creep-rupture strength properties and because of its corrosion resistance (Ref. 2). This alloy and its weldability have, therefore, been the subject of various investigations (Refs. 1-6).

It has been possible to increase the notch impact strength of the base metal by reducing the sulfur content (Ref. 7). To the authors' knowledge, however, the notch impact strength of the weld metal has not yet been improved to the same extent by using conventional arc welding techniques (Ref. 8). On the other level, the impact strengths of the welded joints of some other steels – *e.g.*, HY90 (Ref. 9) and 2.25%Cr-1%Mo steel (Ref. 10) – were improved by electron beam welding. Thus it appeared worthwhile to examine the use of EB welding to attain impact strength properties for 12%Cr steels, since EB welding methods have already reached a stage of practical application (Refs. 9, 11-15).

The electron beam welding of 12%Cr steels has given especially good results (Refs. 11-13), although some difficulties were also reported (Ref. 16). It has been emphasized that high precision welding can be performed, since the energy concentration is high and no preheating is necessary (Ref. 12). Reduced production costs make this method even more attractive (Ref. 12). However, published reports (Refs. 11-13) on the weldability of 12%Cr steels joined by EB welding do not give much information concerning mechanical properties. Therefore, it was the aim of research described here to determine the mechanical properties of EB welded joints in Fe-0.2%C-12%Cr-1%Mo alloy steel in both the tempered condition (2 h at 740°C/1364°F) and the tempered plus aged condition (2 h at 740°C/1364°F plus 5000 h at 550°C/1022°F). Along with mechanical behavior, some metallographic aspects were also investigated.

Experimental Procedures

The base material was steel with a

Table 1—Chemical Composition of Base Metal, Wt-%

C	0.19	Ni	0.73
Cr	11.75	P	0.019
Mo	0.95	S	0.014
Mn	0.68	Si	0.18
V	0.34	Cu	0.18

Table 2—Electron Beam Welding Conditions

Beam current, mA	40
Accelerating voltage, kV	140
Travel speed, mm/s	5
Deflection:	
Longitudinal, mm	1.1
Transverse, mm	0.8
Frequency, cps	76

nominal conposition of 0.2%C, 12%Cr, and 1%Mo, forged to a thickness of 270 mm (10.63 in.). The chemical composition is given in Table 1 and corresponds to the West German standard steel X 20 CrMoV 121. The as-delivered material was air cooled from 1030°C (1886°F) to room temperature and tempered at 760°C (1400°F) for 6 h. Next, four pairs of 21 mm (0.83 in.) thick, 200 mm (7.87 in.) long and 50 mm (1.97 in.) wide plates were machined from the base material. The two plates of each pair were then tack welded to each other at their ends by arc welding. Finally, the plates were electron beam welded under high vacuum so as to form four 200 mm (7.87 in.) long welded plates with the EB weld parallel to the main forging direction.

The EB welding conditions are shown in Table 2. The welds were made at the location of maximum beam density on the upper surface of the plates. After welding, a tempering treatment at 740°C (1364°F) for 2 h was carried out. Charpy V-notch and tensile specimens were machined from the EB welded plates as illustrated in Fig. 1.

Specimens were taken from the center of the plate thickness. The EB welded specimens were oriented transverse to the weld, while the all-base-metal specimens were taken transverse to the main forging direction. The Charpy V-notch specimens were notched in a direction perpendicular to the plate surface. The all-base-metal Charpy V-notch specimens and Charpy V-notch specimens of the EB welded joint with the notch at weld center were tested at temperatures ranging from −60°C (−76°F) to 550°C (1022°F). Charpy V-notch specimens with the notch off the EB weld center line were tested at room temperature. Tensile specimens of the EB welded joint (smooth, and notched at weld center) and the base metal (smooth, and notched) were tested at room temperature and at 550°C (1022°F).

EB welded plate samples (tempered condition) were heat treated at 550°C (1022°F) for 5000 h. Charpy V-notch specimens with the transverse EB welds (notched at the weld center) as well as all-base-metal Charpy V-notch specimens were then machined from these samples. Testing was carried out at temperatures up to 550°C (1022°F).

Light microscopy and hardness measurements (Vickers diamond pyramid hardness with a 200 gram load) were carried out on cross sections transverse to the EB weld for the as-welded condition and after tempering for 2 h at 740°C (1364°F). Furthermore, in the as-welded condition, a midsection parallel to the plate surfaces was examined by light microscopy. The microsections were prepared by polishing with a 0.25 μm diamond spray and etching with an alcoholic solution of picric acid and hydrochloric acid, *i.e.*, 50 g picric acid, 5 ml hydrochloric acid, 1000 ml ethyl alcohol.

Microprobe analysis was carried out on a cross section of an EB welded plate in the tempered condition. The instrument used was a "Cameca MS 46." The accelerating voltage was 13 kV, and the beam current was 0.17 mA. A line scan across the EB weld was achieved by moving the specimen continuously with a motor drive with a travel speed of 0.020 mm/min (0.00079 ipm) while detecting CrK_α and MoL_α radiation with the aid of a gas flow proportional counter.

Selection of the CrK_α and MoL_α peaks was performed using a pentaerythritol (PET) and a potassium hydrogen phthalate (KAP) crystal, respectively. X-ray intensities were determined as average values over counting periods of 5 min, corresponding to a distance of 0.1 mm (0.0039 in.) on the specimen. The local Cr and Mo contents were evaluated from the x-ray data using the base metal as a reference.

Results

Figure 2 shows experimental Charpy V-notch energy data of the EB welded plates (base metal and welded joints with the notch at the weld center) of the alloy Fe-0.2%C-12%Cr-1%Mo, in the tempered condition (2 h at 740°C or 1364°F) and after subsequent aging (5000 h at 550°C or 1022°F), plotted against testing temperatures ranging from −60°C (−76°F) to 550°C (1022°F). The diagram shows that, in the tempered condition,

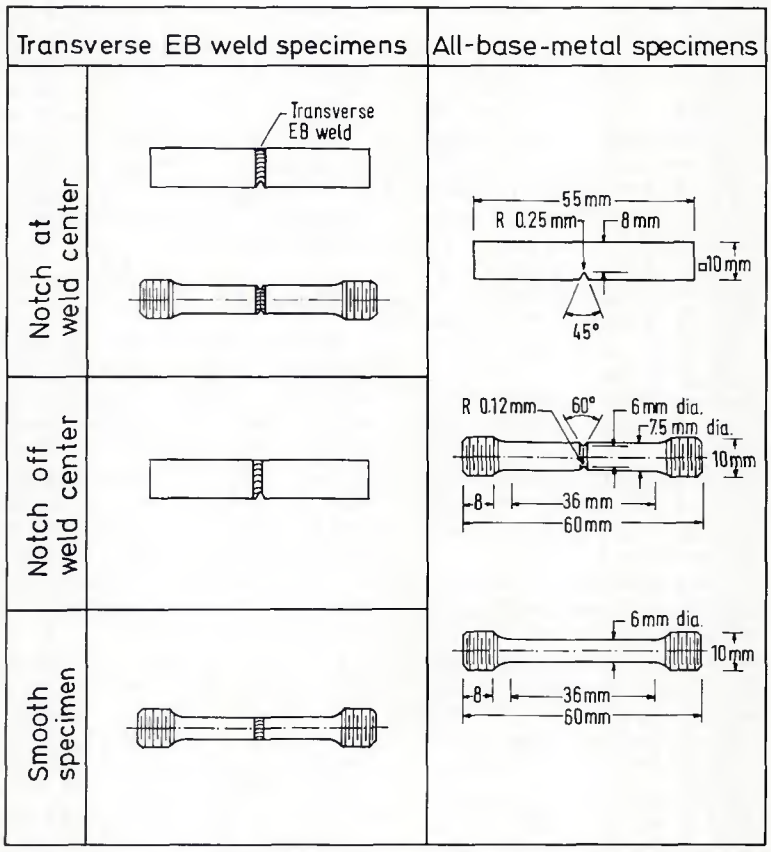

Fig. 1—Specimen designs; comparable transverse EB weld and all-base-metal specimens have the same dimensions

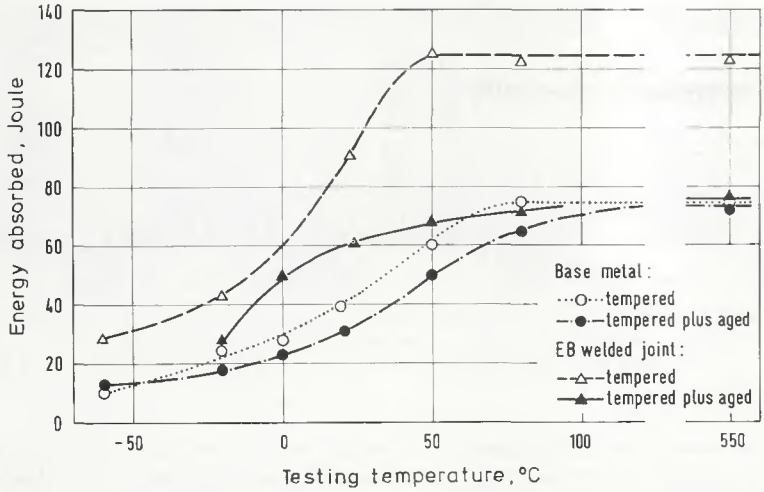

Fig. 2 — Experimental Charpy V-notch energy of weld joint (notch at weld center) and base metal of EB welded alloy Fe-0.2%C-12%Cr-1%Mo plates as a function of testing temperature. Conditions: tempered (for 2 h at 740°C/1364°F) and tempered plus aged for 2 h at 740°C (1364°F) + 5000 h at 550°C (1022°F). Orientation of EB welded joint specimens: transverse to EB weld; orientation of base metal specimens: transverse to main forging direction

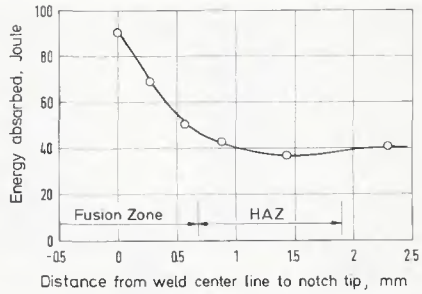

Fig. 5 — Experimental Charpy V-notch energy of the weld joint of EB welded alloy Fe-0.2%C-12%Cr-1%Mo plate tempered for 2 h at 740°C (1364°F) as a function of notch location; testing temperature was 21°C (70°F). Specimen orientation: transverse to EB weld

the Charpy V-notch energies of transverse EB weld specimens notched at the weld center exceeded those of the base metal specimens in the whole temperature range investigated.

The upper shelf energy of the EB welded joint was much higher compared to that of the base metal. After subsequent long time aging for 5000 h at 550°C (1022°F), the Charpy V-notch energy of the EB welded joint dropped to considerably lower values, whereas the Charpy V-notch energy of the base metal did not decrease to a comparable extent. However, the Charpy V-notch values of the EB welded joint are still greater than those of the base metal in the temperature range of −20°C (−4°F) to 80°C (176°F) although the upper shelf levels are virtually equal.

Figures 3 and 4 show the crack paths in the midplane of the transverse EB weld Charpy V-notch specimens notched at the weld center, in the tempered condition and after subsequent aging, respectively. It can be seen from Fig. 3 that, in the case of the tempered condition, the crack was deflected toward the heat-affected zone (HAZ) of the base metal at temperatures higher than 23°C (73°F). At −60°C (−76°F) and −20°C (−4°F) however, the crack was directed right through the center of the EB weld.

Figure 4 shows that, for the tempered plus aged condition at temperatures higher than 0°C (32°F), the cracks in the transverse EB weld Charpy V-notch specimens were deflected into the HAZ. Also in one case, at 550°C (1022°F) the crack reached the unaffected base metal (Fig. 4F); at −20°C (−4°F), the crack took a course along the boundary of the EB weld metal instead of into the HAZ.

Figure 5 shows the Charpy V-notch energy of transverse EB weld specimens in the tempered condition for a constant

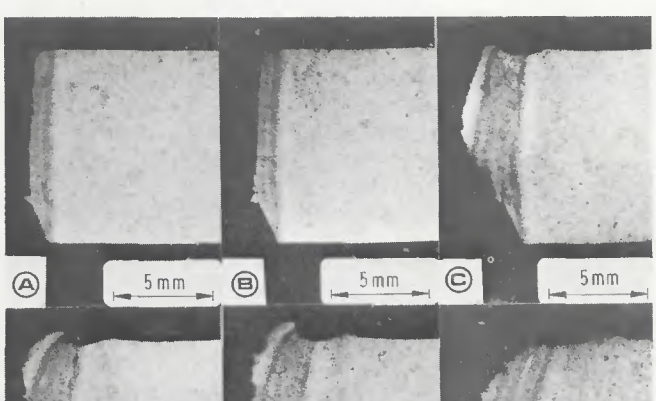

Fig. 3 — Crack paths in the midplanes of Charpy V-notch specimens of the weld joint of an EB welded alloy Fe-0.2%C-12%Cr-1%Mo plate tempered for 2 h at 740°C (1364°F). Etchant: alcoholic 5% picric acid — 0.5% hydrochloric acid solution. Specimens were notched at weld center and tested at: A) −60°C (−76°F); B) −20°C (−4°F); C) 23°C (73°F), D) 50°C (122°F), E) 80°C (176°F), F) 550°C (1022°F). Test results are shown in Fig. 2

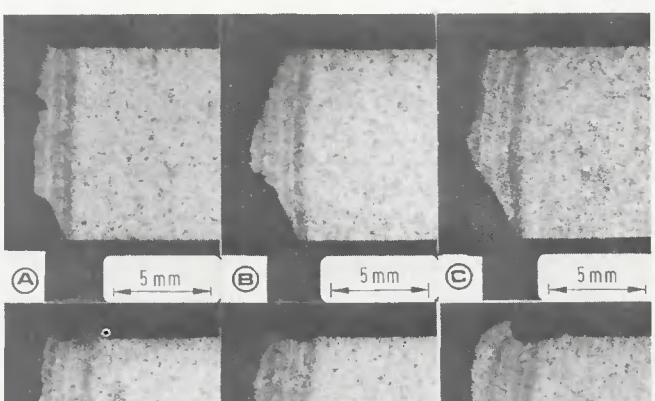

Fig. 4 — Crack paths in the midplanes of Charpy V-notch specimens of the weld joint of an EB welded alloy Fe-0.2%C-12%Cr-1%Mo plate in the tempered plus aged condition, i.e., 2 h at 740°C (1364°F) + 5000 h at 550°C (1022°F). Etchant: alcoholic 5% picric acid — 0.5% hydrochloric acid solution. Specimens were notched at weld center and tested at: A) −20°C (−4°F), B) 0°C (32°F), C) 24°C (75°F), D) 50°C (122°F), E) 80°C (176°F), F) 550°C (1022°F). Test results are shown in Fig. 2

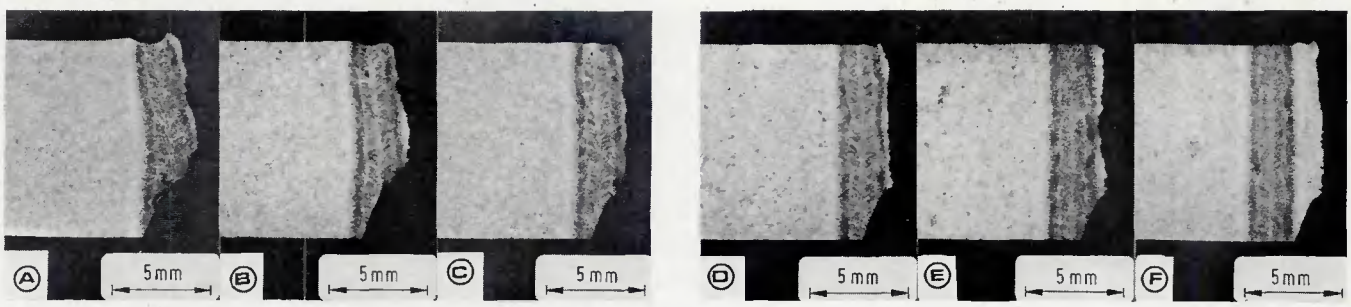

Fig. 6 — Crack paths in the midplanes of Charpy V-notch specimens of the weld joint of an EB welded alloy Fe-0.2%C-12%Cr-1%Mo plate tempered for 2 h at 740°C (1364°F). Etchant: alcoholic 5% picric acid — 0.5% hydrochloric acid solution. Specimens were tested at 21°C (70°F); the distance between notch tip and weld center line was: A — 0.00 mm (0.000 in.), B — 0.27 mm (0.011 in.), C — 0.57 mm (0.022 in.), D — 0.88 mm (0.035 in.), E — 1.43 mm (0.056 in.), F — 2.29 mm (0.090 in.). Test results are shown in Fig. 5

testing temperature of 21°C (70°F) but different notch locations. It can be seen that, with increasing distance between the notch tip location and the weld center line, the Charpy V-notch energy markedly decreases and then seems to increase slightly until the value of the base metal is reached.

Figure 6 shows the crack paths in the midplane of the transverse EB weld Charpy V-notch specimens with notch off weld center. It can be seen that, for distances from the weld center line to the notch tip of 0.88 mm (0.035 in.) and smaller, the crack was deflected away from the notch tip toward the nearby heat-affected zone and finally ended in a path about 1.4 mm (0.055 in.) off weld center (Fig. 6A-C). At distances from weld center line to notch tip of 1.43 mm (0.056 in.) and 2.29 mm (0.090 in.), the crack ran right through the HAZ or the base metal, respectively, without being deflected (Fig. 6E, F).

Figure 7 compares the transverse weld Charpy V-notch data of the EB welded joint of the alloy Fe-0.2%C-12%Cr-1%Mo (specimens notched at the weld center) with transverse weld Charpy V-notch data (Ref. 6) of the weld metal (similar to Fe-0.2%C-12%Cr-1%Mo) of a submerged arc welded joint. Data, both in the tempered condition and in the condition after subsequent aging for 5000 h at 550°C (1022°F), were included.

The submerged arc welding was carried out using a filler metal similar to Fe-0.2%C-12%Cr-1%Mo; the preheating temperature was between 220°C (428°F) and 250°C (482°C). The submerged arc weld was cooled down to between 125°C (257°F) and 135°C (275°F) and subsequently tempered at 740°C (1364°F) for 10 h (Ref. 6). It can be seen that, in the whole temperature range considered, *i.e.*, −60°C (−76°F) to 550°C (1022°F), the Charpy V-notch energy values obtained for submerged arc welding are below the Charpy V-notch energy vs. temperature curve for EB welding. This is the case for the tempered condition as well as after subsequent aging at 550°C (1022°F) for 5000 h.

Table 3—Experimental Tensile Strength of the Weld Joint and Base Metal of an EB Welded Plate of Alloy Fe-0.2%C-12%Cr-1%Mo Tempered for 2 h at 740°C (1364°F)

Specimen tested		Testing Temperature, °C (°F)	Tensile strength, MPa (ksi)
All-base-metal specimen	Smooth	21 (70)	711 (103)
		550 (1022)	386 (56)
	Notched	21 (70)	963 (140)
		550 (1022)	580 (84)
Transverse EB weld specimen	Smooth	21 (70)	710 (103)
		550 (1022)	381 (55)
	Notched	21 (70)	987 (143)
		550 (1022)	592 (86)

Tensile test results are listed in Table 3. The tensile strengths of the notched specimens refer to the area under the notch which is equivalent to the cross-sectional area of the smooth specimens. It can be seen that all-base-metal tensile tests and transverse EB weld tensile tests yielded virtually the same results both at room temperature and at 550°C (1022°F). The two smooth transverse EB weld specimens (tested at room temperature and 550°C/1022°F) fractured in the base metal about 8 mm (0.31 in.) away from the weld center.

The microstructure of the EB welded joint is shown in Fig. 8 for the as-welded condition and the tempered condition. It can be seen that the EB weld metal solidified primarily as a dendritic structure. In addition, dendritic growth occurred transverse to the travel direction of the electron beam at both sides of

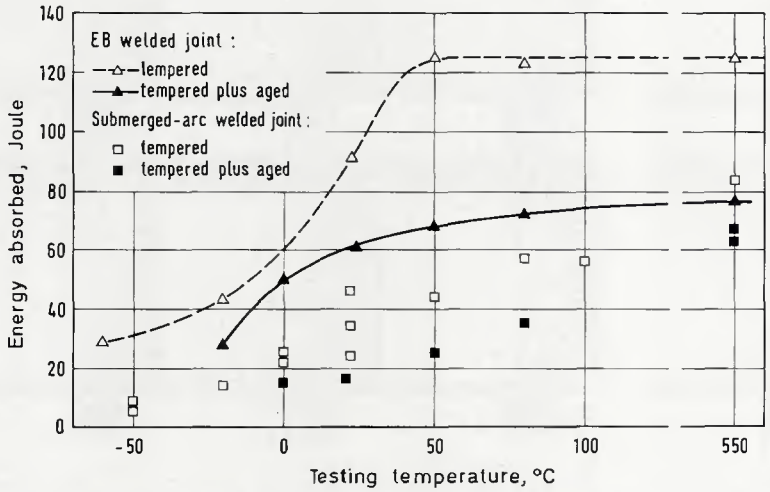

Fig. 7 — Charpy V-notch data for weld joints of EB welded alloy Fe-0.2%C-12%Cr-1%Mo plates (notch at weld center) compared with Charpy V-notch data (Ref. 6) for a submerged arc welded joint using a filler metal similar to Fe-0.2%C-12%Cr-1%Mo. Conditions: tempered at 740°C (1364°F) and tempered plus aged at 550°C (1022°F) for 5000 h. Specimen orientation: transverse to weld

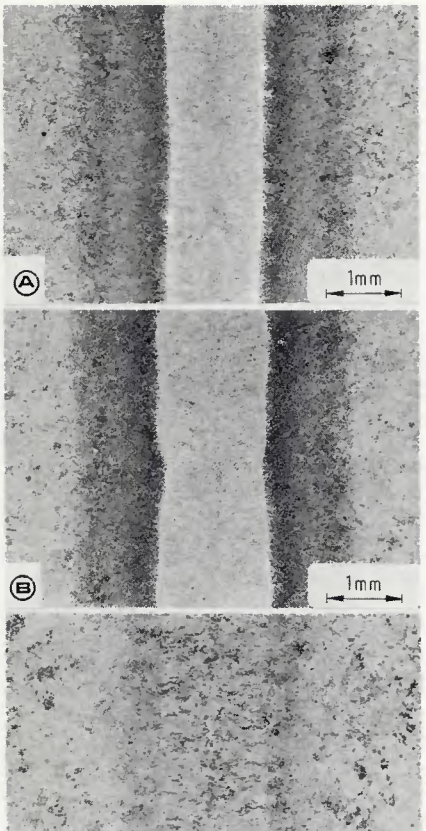

Fig. 8—Microstructures of weld joint in EB welded alloy Fe 0.2%C-12%Cr-1%Mo plate at the center of plate thickness: A—as-welded condition, transverse cross section; B—as-welded condition, midsection parallel to plate surface; C—tempered for 2 h at 740°C (1364°F), transverse cross section. Etchant: alcoholic 5% picric acid—0.5% hydrochloric acid solution

the weld and parallel to it at the center of the weld—Fig. 8B.

A visible effect of the heat input during EB welding on the microstructure of the base metal can be detected up to a distance of about 1.9 mm (0.075 in.) from the weld center line—Figs. 8A, B. The width of the fusion zone is about 1.35 mm (0.053 in.). Light microscopy further revealed a martensitic structure of the EB weld metal in the as-welded condition, with only negligible remains of δ-ferrite being detectable.

Figure 9 shows a microhardness traverse across the EB weld for the as-welded condition and the tempered condition. It can be seen that the hardness of the EB weld is greatly reduced by tempering but still exceeds the hardness of the base metal. Figure 9 also shows that the microhardness of the base metal is affected by the heat input during EB welding up to a distance of about 1.9 mm (0.075 in.) from the weld center line.

The results of the x-ray microanalysis are shown in Fig. 10 (tempered condition). The local chromium and molybdenum content is plotted as a function of distance from weld center line. The plot shows no macrosegregation of Cr and Mo across the weld.

Discussion

The main purpose of this investigation was to determine the mechanical properties of EB welded joints in alloy Fe-0.2%C-12%Cr-1%Mo. Examination of the Charpy V-notch energy using specimens notched at weld center indicates that, in the tempered condition, the EB welded joint has an impact strength which is much higher than that of both the base metal and weld metal of a submerged arc welded joint taken for comparison. After subsequent long time aging at 550°C (1022°F), the impact strength of the EB welded joint still exceeds or at least is equivalent to that of the base metal and the submerged arc weld metal in the temperature range considered. Examination of the impact strength of specimens (in the tempered condition) with the notch off the weld center further confirmed a superior impact strength behavior of the EB welded joint compared with that of the submerged arc weld.

It should be noted that, in contrast to the data of the submerged arc weld, the impact strengths at temperatures higher than 0°C (32°F) for EB welded joints in both the tempered condition and condition after subsequent aging may not display the behavior of the EB weld metal, itself. This is true even if the specimens are notched exactly at the weld center, since crack deflection extended into the HAZ.

Crack deflection may partially be the reason for the relatively high impact strength values of the EB welded joints. On the other hand, crack deflection is evidence for a superior impact strength of the EB weld metal, itself. This is confirmed for the specimens in the tempered condition by the test results obtained in the low temperature range from −60°C (−76°F) to −20°C (−4°F). At these low temperatures, the EB weld metal, itself, could be tested directly, because no deflection of the crack took place. This result clearly indicates that not only the EB welded joint but also the EB weld metal itself has a greater impact strength than that of the base metal used and that of the submerged arc weld metal taken for comparison.

The tensile test results show that tensile properties of the EB welded joint (in the tempered condition) are, at least, not worse than that of the base metal. Moreover, the tensile tests (at room temperature and 550°C/1022°F) of the smooth specimens of the EB welded joint indicate that the weld metal has a tensile strength higher than that of the base metal since fracture took place in the base metal. This corresponds to the fact that the microhardness of the EB weld metal (in the tempered condition) is greater than that of the base metal.

A very important point is the corrosion resistance of the EB welded joint; this can only be ensured for chromium contents exceeding 11 wt-% (Ref. 5). On the other hand, 13 wt-% Cr must not be exceeded to ensure that the steel will be fully transformable into martensite by air cooling (Ref. 5). Results of the microprobe analysis show that the limiting conditions for the chromium content are fulfilled everywhere across the EB weld. In contrast to this finding, considerable macro-

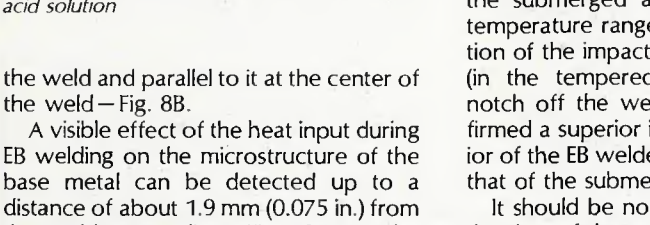

Fig. 9—Microhardness traverse across the weld in transverse cross sections of EB welded alloy Fe-0.2%C-12%Cr-1%Mo plate at the center of plate thickness; as-welded condition and tempered for 2 h at 740°C (1364°F)

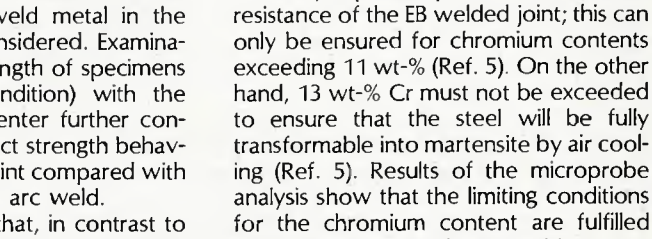

Fig. 10—Microprobe line scan across the weld in a transverse cross section of EB welded alloy Fe-0.2%C-12%Cr-1%Mo plate at the center of plate thickness; tempered for 2 h at 740°C (1364°F)

segregation in the EB welded joint of a modified 12% Cr steel (up to 14% Cr) was reported elsewhere (Ref. 16).

Conclusion

Electron beam welds in alloy Fe-0.2%C-12%Cr-1%Mo were examined with respect to mechanical properties along with some metallographic features. The results of these investigations are summarized as follows:

1. The impact strength of the EB welded joint (tempered at 740°C (1364°F) for 2 h) was found to exceed that of the base metal, as well as that of a submerged arc welded joint made for comparison, at testing temperatures up to 550°C (1022°F). This remained true, in the transition temperature range, after aging at 550°C (1022°F) for 5000 h, whereas the upper shelf levels were found to be virtually equal after aging.
2. Tensile strengths at room temperature and at 550°C (1022°F) of the EB welded joint (in the tempered condition) were higher than those of the base metal, since smooth transverse EB weld tensile specimens fractured in the base metal.
3. Macrosegregation of chromium and molybdenum was not detectable in the EB weld metal.
4. Light microscopy on microsections of the EB weld in the as-welded condition revealed a virtually completely martensitic structure of the EB weld metal.

Acknowledgment

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Stress Indices and Flexibility Factors for Concentric Reducers
by E. C. Rodabaugh and S. E. Moore

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Finite Element Analysis of Eccentric Reducers and Comparisons with Concentric Reducers
by R. R. Avent, M. H. Sadd, and E. C. Rodabaugh

This report was developed to provide stress indices for eccentric reducers, and includes recommendations for relatively minor work changes in the NB-3680 portion of the ASME Code which would extend the coverage to include eccentric reducers.

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