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Mechanical Properties of Electron Beam Welds of Heavy Section Steel Plates†

Yoshiaki ARATA *, Michio TOMIE **, Mutsuo NAKANISHI *** and Jun FURUSAWA ***

Abstract

The electron beam (EB) welding process has been applied to heavy section steel plates mainly because of its high productivity and low heat input. There are, however, several problems to be solved. In this study, mechanical properties (mainly toughness) of EB welds have been investigated for nine heavy section steel plates. Correlations have been found between toughness and carbon content of EB welds. The toughness improved with reducing carbon content, especially in the as-welded condition. The toughness of steels with high carbon content ($C \geq 0.24\%$) is extremely poor owing to the formation of high carbon martensitic island, and modification of chemical composition is required for these steels. Therefore B treated steel with low C content could be expected to have improved toughness of EB welds.

KEY WORDS: (Mechanical Properties) (EB Welds) (Heavy Section Steel Plates) (Al-B Treated Steel) (EB Welding Process) (Hardness)

1. Introduction

There are several problems to be solved in the welding process of heavy section steel plates used for pressure vessels of nuclear plants and for reactor vessels of chemical plants. For example, long welding time is required and complicated thermal cycles deteriorate the mechanical properties of welds.

As a means of reducing the overall welding time, application of the electron beam welding process (hereafter called EB), which makes it possible to obtain deep penetration depth by one pass welding, has been studied.

Although a number of problems remained unsolved in the application of the EB welding process of heavy section steel plates, remarkable technical breakthroughs have been made recently by the introduction of a vacuum type high energy EB welding machine. The machine is highly effective and offers welds superior to welds done by conventional welding machines. As this fact is recognized among the industry concerned, the fields for application of the vacuum type high energy EB welding machine have been widely extended. As previously described however, application of the EB welding process to heavy section steel plates still imposes a number of problems to be solved[1-3].

The main defects observed in EB welding are A-porosity and blowhole. It is widely known that the occurrence of these defects are affected by the welding parameters and also the gaseous compositions of the steel plates[4-6]. Lack of adequate imformation on mechanical properties of EB welds may be cited as another problem to be tackled.

Therefore, in this study, mechanical properties of EB welds (mainly toughness) have been investigated for nine heavy section steel plates.

2. Experimental Method

Investigations have been made to clarify the mechanical properties of EB welds for nine (9) heavy section steel plates, to which the EB welding process is expected to be applied.

Table 1 shows chemical composition and mechanical properties of commercial steels used in this study. These steels received demagnetization treatment below 30 Gauss.

The EB welding machine used in this study was a high vacuum type welding machine with maximum capacity of 75 kW (150 kV). Horizontal position welding was carried

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* Professor
** Associate Professor
*** Sumitomo Metal Industries, Ltd.

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Table 1 Chemical composition and mechanical properties of materials used

	Steel	Chemical composition (wt %)											Plate thickness	TS_{RT}	vTs
		C	Si	Mn	P	S	Cu	Ni	Cr	Mo	V	Nb	mm	MPa	°C
A	A387 Gr. 22	0.12	0.25	0.45	0.020	0.010	—	—	2.17	0.88	—	—	100	624	-65
B	A387 Gr. 11 (O)	0.13	0.69	0.60	0.021	0.012	—	—	1.39	0.53	—	—	100	539	+22
C	A387 Gr. 11 (B)	0.15	0.55	0.59	0.011	0.003			1.38	0.54	B:0.0008		75	631	-23
D	A533B	0.19	0.24	1.40	0.023	0.003	—	0.58	—	0.53	—	—	71	644	-37
E	HT80 (S)	0.19	0.45	1.10	0.008	0.009	—	—	0.83	0.42	—	—	75	841	-92
F	HT80 (N)	0.12	0.28	0.84	0.014	0.007	0.23	0.88	0.62	0.43	0.04	—	100	788	-27
G	A633A	0.15	0.24	1.14	0.016	0.004	—	—	—	—	—	0.02	100	479	-27
H	A588A	0.13	0.31	1.12	0.023	0.009	0.22	—	0.35	—	0.04	—	100	552	-11
I	A516 Gr. 70	0.23	0.25	1.13	0.017	0.005	0.31	0.21	—	—	—	0.03	94	583	+ 5

Table 2 Welding conditions

Welding position	Accelerating voltage (kV)	Beam current (mA)	Welding speed (cm/min)	Heat input (kJ/cm^2)	Focus position (a_b)	Beam oscillation condition	
						Frequency (kHz)	Amplitude (mm) X direction* Y direction
Horizontal	150	170∿290	15	12.0~17.7	1.0	2	1.5* 0.7 0.7* 0.3 (F.H steel)

Table 3 Post weld heat treating conditions

Steel	Standard condition			Temper parameter range investigated
	Temperature (°C)	Time (h)	Temper parameter [P] T(20 + log t) x10^{-3}	
A	690	8	20.1	19.5 ~ 21.4
B	710	8	20.6	19.3 ~ 21.1
C	700	9	20.4	19.6 ~ 20.8
D, E, G, H, I	615	4	18.3	—

out by using the bead on plate method. **Table 2** shows the welding condition. They were selected to obtain proper welds of full penetration by one pass with a 4 mm wide weld bead as the object. The beam profile of the EB welding machine used in this study is similar to that of a parallel beam of a higher capacity. Therefore, the effect of focus position on penetration is hardly noticeable. From the above result, ab parameter was fixed at 1.0.

Standard heat input is assumed within a range from 15.2 to 16.1 kJ/cm^2. To know the effect of heat input on the mechanical properties of welds, heat input was changed over the range from 12.0 to 17.7 kJ/cm^2. The mechanical properties of welds were investigated both in the as-welded condition and after post weld heat treatment (PWHT) [stress relief (SR) treatment].

Table 3 shows various conditions of PWHT. As for steel A, B and C various conditions of PWHT in addition to the standard were used.

3. Experimental Results and Review

Figure 1 shows a cross-section of the macrostructure and bead appearance. Favorable bead appearance could be obtained without any backing plate. The test results were obtained by using the standard heat input (15.2 through 16.1 kJ/cm^2) for items 3.1 through 3.5. The effect of heat input on mechanical properties is discussed in item 3.6.

3.1 Chemical composition of weld metal

Figure 2 shows the relation between the amount of manganese in base metal and EB weld metal. Manganese (Mn) is an element with high vapor pressure. As observed in the test result, the amount of Mn in the surface side of EB weld metal (10 mm from the surface) was reduced by a factor of about 0.8 of that in base steel. However,

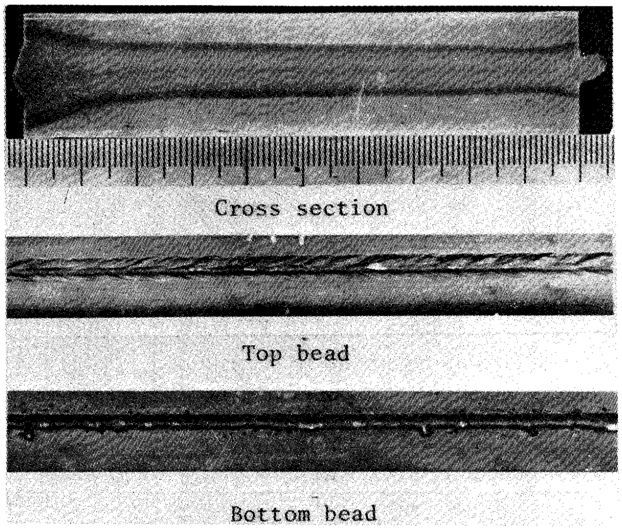


Fig. 1 Macrostructure of cross section and bead appearance of EB welds (plate thickness 100 mm, heat input 15.6 kJ/cm²)

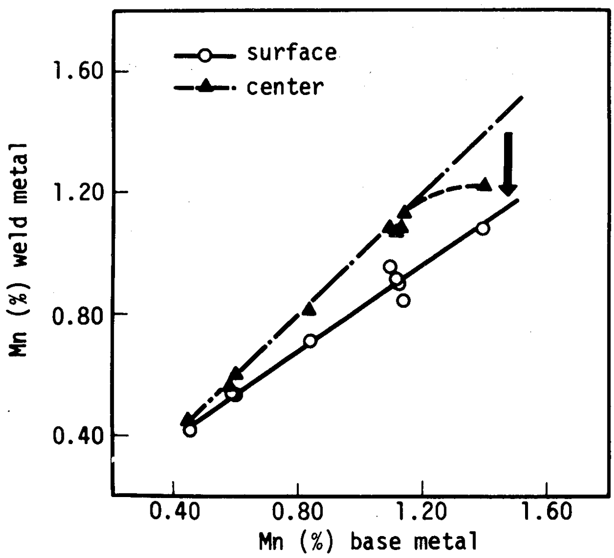


Fig. 2 Relation between the amount of manganese in base metal and in EB weld metal

the same amount of Mn can be observed both in base metal and EB weld metal in the center of the plate thickness up to 1.2%.

The test result reveals that there exists no difference of amount for other components between base metal and weld metal including gases (O, N) and impurity elements (P, S).

3.2 Tensile properties of EB welds

The tensile properties of EB welds at RT were studied by using the test piece shown in **Fig. 3**. Fracture occurred only on the side of the base metal either as welded or

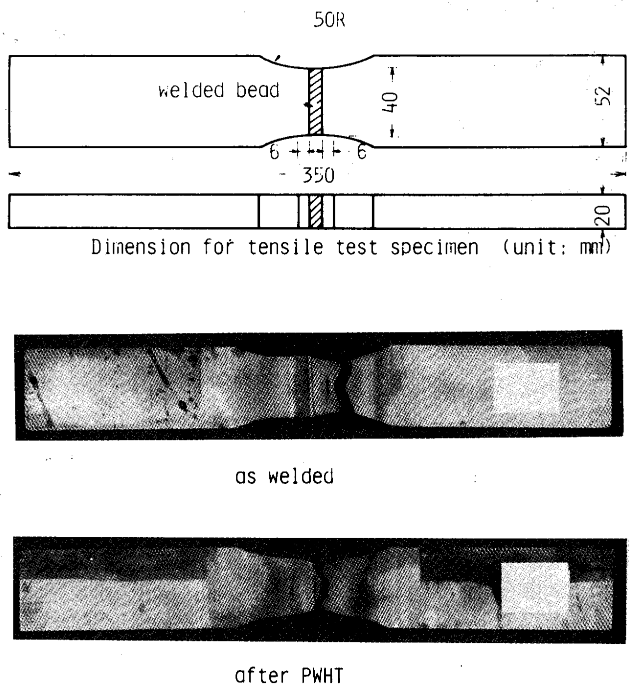


Fig. 3 Dimension of tensile test specimen and example of external appearance

after PWHT. As shown in **Fig. 4**, the tensile strength exceeds the lower limit of the specified strength both as welded and after PWHT.

Steels A, D and E exceed the upper limit of specified strength in as welded condition, however the strength after PWHT remain within the range of specification. Therefore, there is no practical problem in application of EB welding process for these steels, because these steels receive PWHT after welding according to the standard. Steel F cannot be applied to locations which require PWHT because SR cracking occurs at the welded bond. Application of steel E with a reduced susceptibility to SR cracking is most desirable in this case.

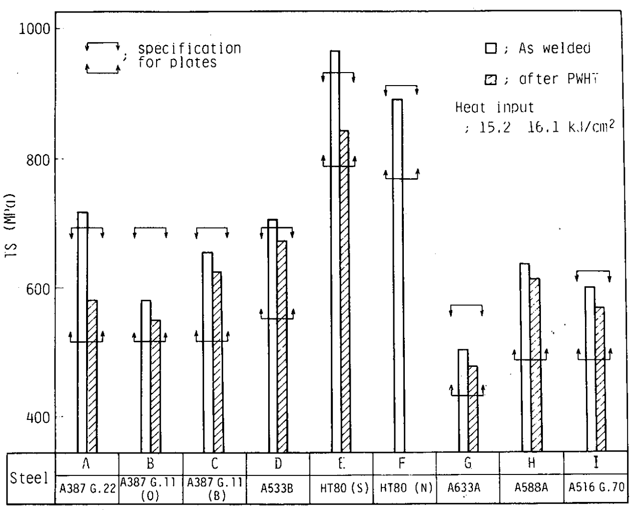


Fig. 4 Tensile test results of EB welds

3.3 Charpy impact properties of EB welds

Charpy impact test piece (JIS No. 4, 2 mm V) was adopted at 1/2t location on the welded section.

Table 4 sums up the properties of 1/2t location. **Figures 5** and **6** show that the toughness decreased with increasing C content in the base metal, both for weld metal and welded bond.

The toughness of most steels is improved by PWHT. The tendency for toughness to decrease with the increase of C content is still observed. The toughness of steel I with high C content remained unchanged even after PWHT. The toughness of steel H is lowered after PWHT and this is considered to be caused by V.

Since the five steels A through E receive PWHT under the requirements of the code, the toughness after PWHT is a criterion for estimation. On the other hand, the four steels F through I are not subject to PWHT under

Table 4 Charpy impact properties of EB welds

Steel		as welded				after PWHT			
		weld metal		welded bond		weld metal		welded bond	
		vTs °C	vEo J	vTs °C	vEo J	vTs °C	vEo J	vTs °C	vEo J
A	A387 Gr. 22	+32	79	-28	245	-74	268	-58	214
B	A387 Gr. 11 (O)	+24	85	+15	51	- 4	134	+15	55
C	A387 Gr. 11 (B)	-12	246	-36	172	-47	198	-36	160
D	A533B	>+80	8	+58	39	0	108	+ 5	80
E	HT80 (S)	+55	41	+54	39	- 6	104	+10	55
F	HT80 (N)	-13	150	-88	161	—	—	—	—
G	A633A	+ 5	92	-17	191	- 5	206	-21	221
H	A588A	+35	47	-20	160	+55	35	+38	23
I	A516 Gr. 70	>+80	8	>+80	8	>+80	7	>+80	5

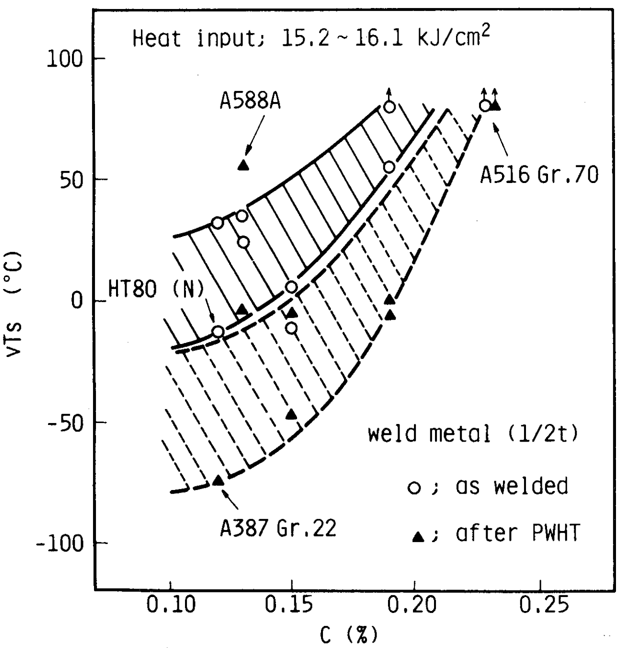


Fig. 5 Relation between C content and the toughness of EB weld metal

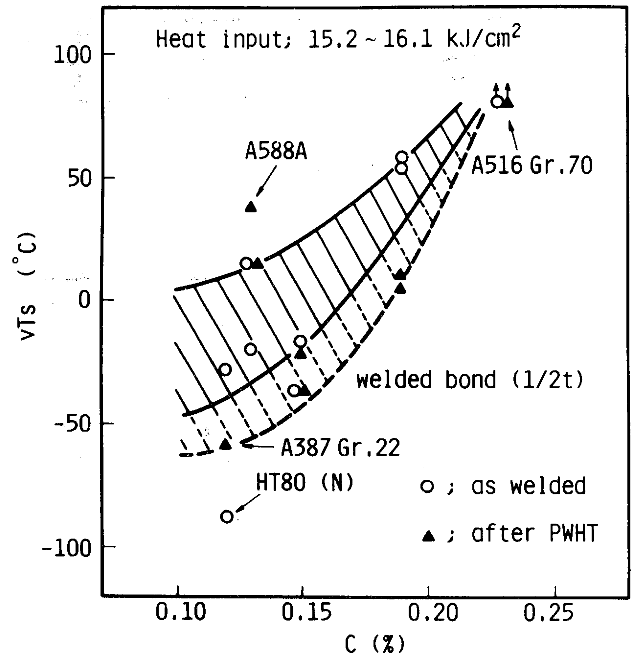


Fig. 6 Relation between C content and the toughness of EB welded bond

certain service conditions and the toughness both in as-welded condition and after PWHT is the criterion for estimation.

The specified values of toughness vary with service temperature and location. If the standard widely used for HT 80 [vEo $\geq$ 54J] is assumed to be a criterion, it is difficult to apply the EB welding process to steel I and it requires some modification of composition, for example, a low carbon content. Therefore B treated steel with low C content[7,8] could be expected to improve the toughness of EB welds. However, there is no substantial problem with the present composition of steels A through E and G, or steels F and H in the as-welded condition to the application for EB welding.

The effect of PWHT on the toughness of EB welds was studied for steel A, B and C. The temper embrittlement properties after step-cooling treatment were also studies. As shown in **Fig. 7** steel A and C indicate stabilized and good toughness in a range of temper parameters (T.P) from 19.5 to 21.5. Steel B shows a lowered toughness, especially when temper parameters are over 21.0. The degree of embrittlement by step-cooling treatment (ΔvTs) is about 30°C for both steel A and B with high P content (0.02%); on the other hand, ΔvTs for steel C with low P content (0.01%) is only 16°C. The toughness of steel A is good enough after step-cooling treatment (vTs is below −10°C); however, the toughness of steel B deteriorates (vTs is from 30 to 40°C) and needs an improved low P content like steel C.

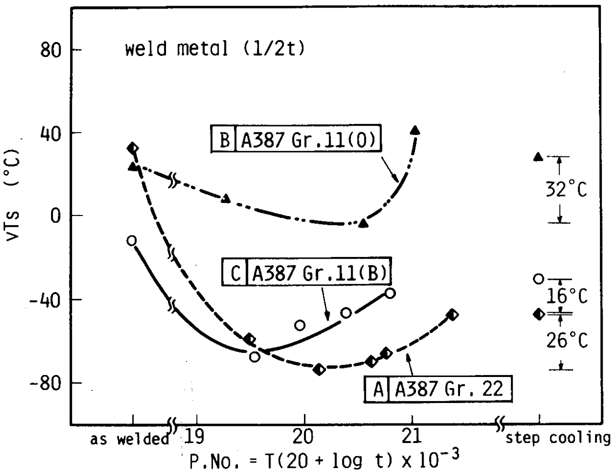


Fig. 7 Effect of temper parameter on toughness and temper embrittlement by step cooling treatment of EB weld metal.

3.4 Hardness of EB welds

Figure 8 shows the hardness distribution of EB welds. EB welds revealed large differences in hardness in a narrow area if left as-welded because the width of the weld bead is only about 4 mm and the zone affected by weld heat is about 2.5 mm wide. This fact reveals the reason why the fracture path deviates from the notch location in the Charpy impact test[3].

Figure 9 shows the relation between PCM* and the maximum hardness of EB welds, as well as the relation between PCM and the maximum hardness of shielded

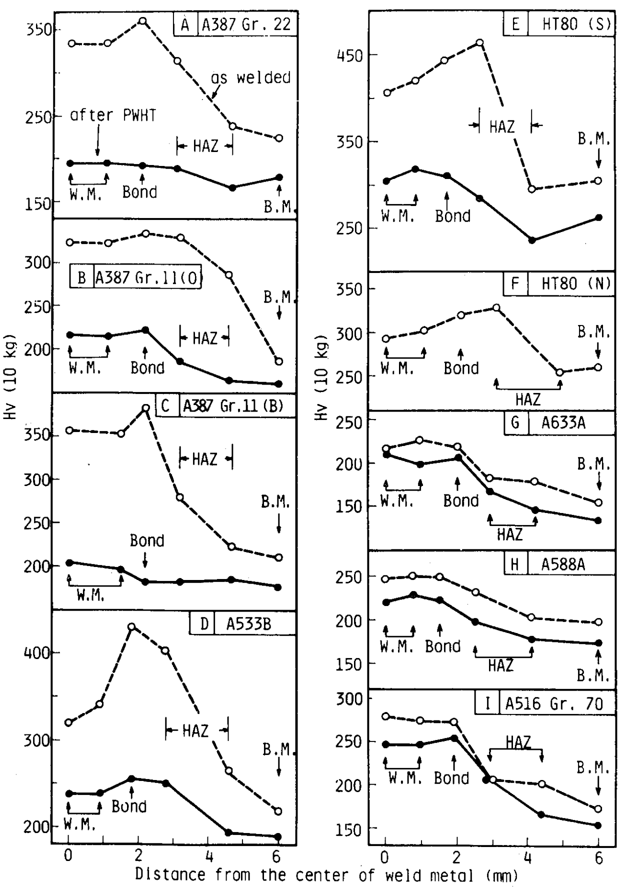


Fig. 8 Distribution of hardness of EB welds

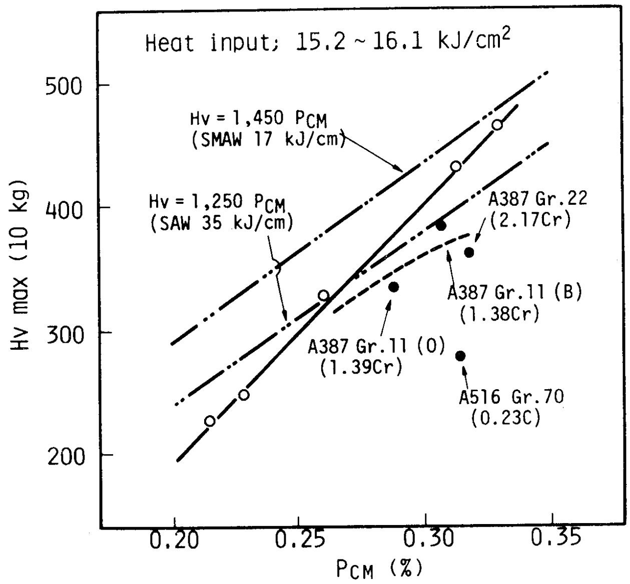


Fig. 9 Relation between PCM and the maximum hardness of EB welds

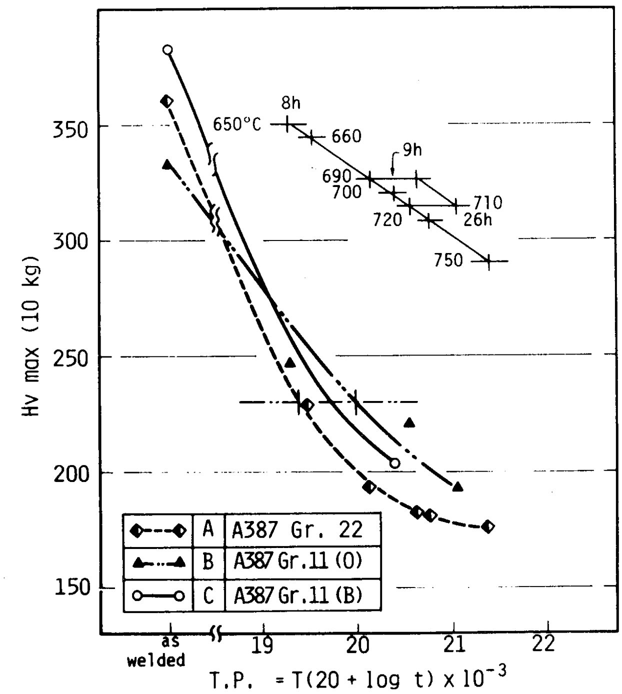


Fig. 10 Relation between temper parameter and the maximum hardness of EB welds

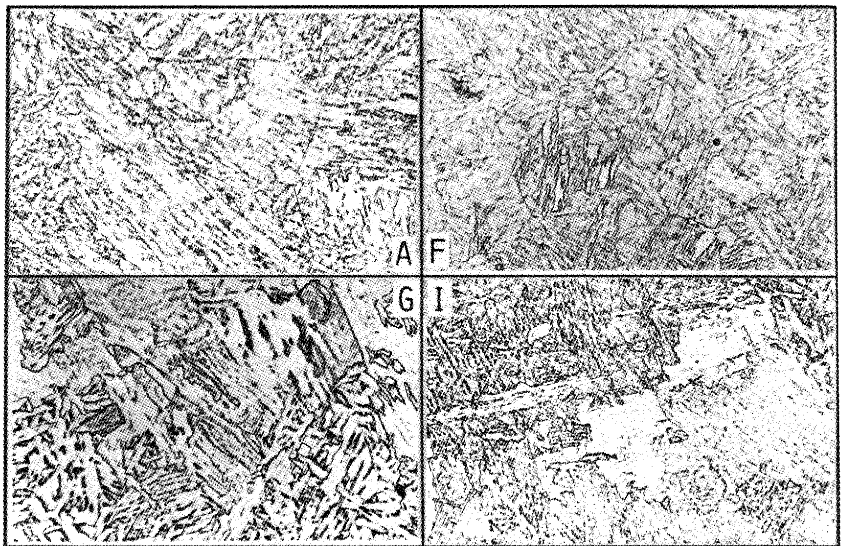
*$P_{CM} = C + Si/30 + (Mn + Cu + Cr)/20 + Ni/60 + Mo/15 + V/10 + 5B$ (%)

metal arc welds with heat input of 17 kJ/cm and the maximum hardness of submerged arc welds with heat input of 35 kJ/cm. EB welds with heat input of 15.2 through 16.1 kJ/cm^2 are considered to have a cooling rate (800 to 500°C, 20 s) like that of submerged arc welds. range of P_{CM} equation ($C \leqq 0.22\%$, $Cr \leqq 1.2\%$) and deviate from linear relation. This is especially noticeable deviated from linear relation. This is especially recognized for high carbon steel I.

Figure 10 shows the relation between the maximum hardness of EB welds and the condition of PWHT for steels A, B and C. If Hv 230 is the maximum hardness aimed for, for example, it will be found that T.P. $\geqq$ 19.4 is required for steel A, T.P. $\geqq$ 20.0 for steel B and T.P. $\geqq$ 19.8 for steel C.

3.5 Optical microstructure of EB welds

Figure 11 is a comparison of optical microstructure and toughness in the center of EB welds. Steel F, with low carbon content and martensite/bainite duplex structure shows the highest degree of toughness in as-welded condition. Steel A, with low carbon content and martensite/bainite duplex structure, indicates a high level of hardness and low toughness in as-welded condition, however, after PWHT exhibits the highest degree of toughness. On the other hand, steel I, with high carbon content and martensite/bainite duplex structure has the lowest level of toughness and shows no improvement with PWHT. Steel G with polygonal ferrite/bainite duplex structure, indicates vTs = 0°C which is an intermediate



Weld metal (1/2t) 20μm	vTs	Steel	A	F	G	I
		as-welded	+32°C	-13°C	+5°C	>+80°C
		after PWHT	-74°C	—	-5°C	>+80°C

Fig. 11 Optical microstructure and the toughness of EB weld metal

toughness between the two classes described above, both in as-welded condition and after PWHT.

3.6 Effect of heat input on the mechanical properties of EB welds

The effect of heat input on the mechanical properties and optical microstructure of welds was studied.

Figures 12 and **13** show the result for steel A. No change of optical microstructure with the change in heat input was observed, which corresponds to the fact that toughness and hardness after PWHT are not affected by heat input. If left as-welded, however, toughness improved and hardness slightly increased with decreasing heat input. Since an increase of hardness is thought to lower toughness, the reduced width of weld bead is something to be considered to improve overall toughness.

It is widely known that the fracture path markedly deviates from the notch location in a Charpy impact test[3)] in a narrow weld bead like in EB welds, described above. As for steel A, the hardness difference between weld metal and base metal is about ΔHv = 100 in as-welded condition and the fracture path is deviated as far as the base metal in the ductile fracture region when the notch location is the center of the weld metal. However, after PWHT the hardness difference is ΔHv = 15 and no deviation in the fracture path is observed. Bead width and hardness

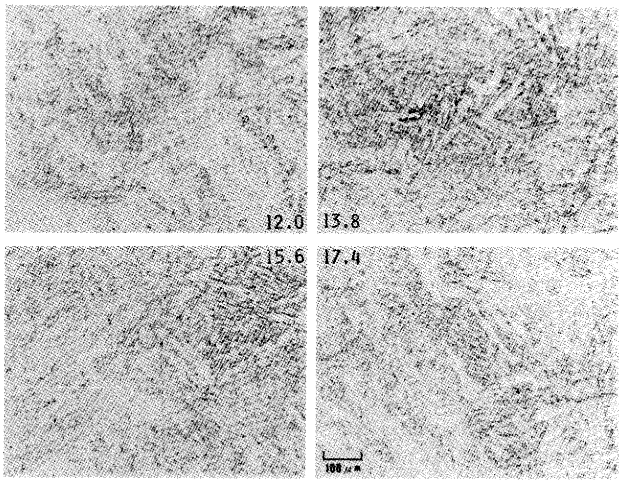


Fig. 12 Effect of heat input on the toughness, maximum hardness and bead width of EB welds

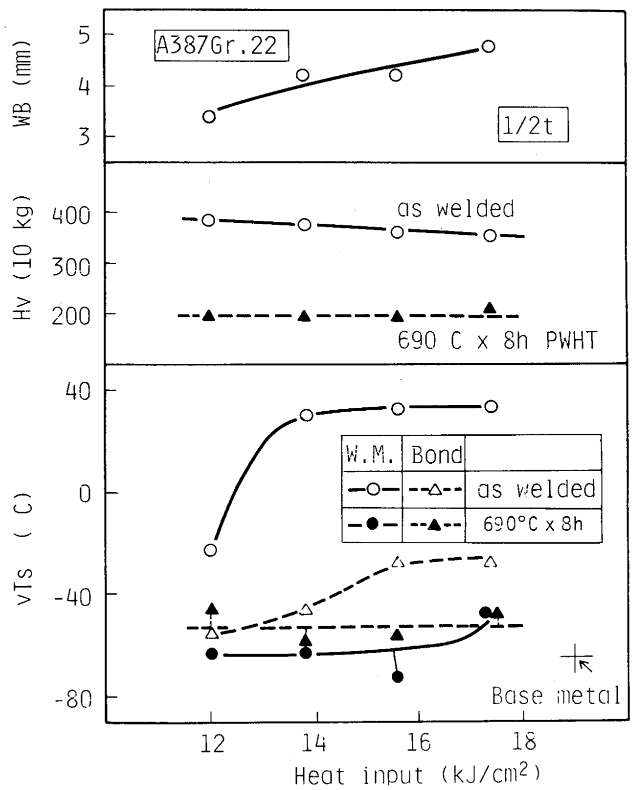


Fig. 13 Effect of heat input on optical microstructure of EB weld metal (2-1/4Cr-1Mo steel, 1/2t, figure in Fig. shows heat input kJ/cm^2)

may be cited as a factor in the deviation of the fracture path from the notch location.

The hardenability parameter (δHv) as described below, and the fracture path parameter (F_p) are used as factors in the deviation of fracture path. Fracture path becomes more easily deviated with an increase in hardenability and fracture path parameters[3].

$$\delta Hv = (Hvw - HvB)/HvB \quad (1)$$

Where Hvw; Hardness of weld metal
HvB; Hardness of base metal

$$F_p = dB/h \quad (2)$$

Where dB; Width of weld bead
h; Remaining thickness length of Charpy specimen

Since the factor h (= 8 mm) is constant in this study, it has been deleted.

Figure 14 shows the relation between toughness in as-welded condition and the value of $P_F = \delta Hv/dB$. The toughness improved with increases in P_F value. Even when the optical micro-structure is not affected by the heat input, the toughness improved by the deviation of the fracture path to the base metal due to a decrease in bead width. However, attention must be paid to the increased possibility of lack of fusion at butt welds, where the width of weld beads is reduced.

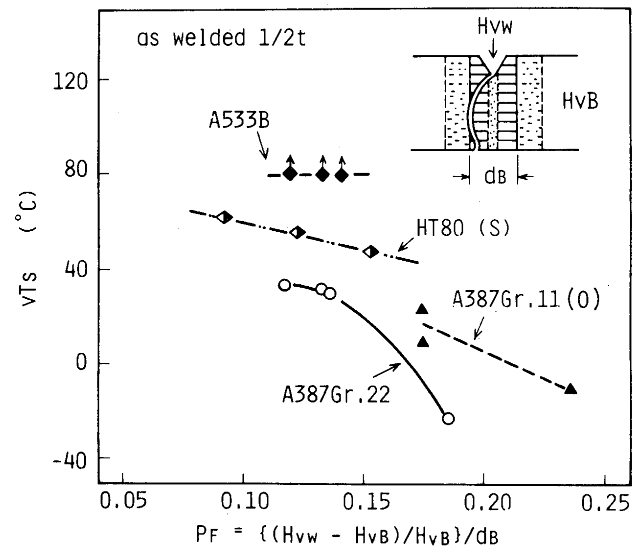


Fig. 14 Relation between P_F and vTs of EB weld metal

4. Conclusions

(1) The toughness of EB welds decreased with increasing carbon content, especially in as-welded condition.

(2) Toughness of EB welds is improved by PWHT in most steels. However, the tendency for toughness to deteriorate with increasing carbon content still remains. The toughness of EB welds for A 516 Gr.

70 with high carbon content (0.23%) still indicates a markedly low value even after PWHT. Decrease in toughness caused by PWHT can be observed at EB welds of A 588 A steel, this is considered owing to V.

(3) Five steels specified to be PWHT by the standard A 387 Gr. 22, A 387 Gr. 11(O), A 387 Gr. 11 (B), A 533B and HT 80 (S) (low SR cracking susceptibility steel) show good mechanical properties of EB weld, therefore they pose no substantial problem to the practical application after PWHT.

(4) Out of four steels which may be used as-welded under some service conditions, the mechanical properties of EB welds for A 633 A are good both in as-welded condition and after PWHT. However, HT 80 (N) and A588 A show excellent mechanical properties of EB welds in as-welded condition, but they are subject to SR cracking and SR embrittlement after PWHT. Application of HT 80 (S) with low susceptibility to SR cracking is considered to cope with SR cracking of HT 80. The toughness of EB welds for A 516 Gr. 70 is markedly low, as described before. Some modification of chemical composition (for example, lowered carbon content) will be required for the application of EB welding. Therefore, B treated steel with lower C content could be expected to have improve the toughness of EB welds.

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