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Mechanical properties of welds of high quality steel by various welding methods

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ABSTRACT: The 590 MPa class tensile strength steel with low yield ratio has been developed to secure ductility of members in particular of high-rise buildings. In the ultimate limit state design, sufficient plastic deformable ability should be guaranteed to increase earthquake-proof security. Thus decrease of yield ratio and increase of weldability are effective procedure for seismic design.

To ensure the major mechanical properties of weld penetration of this high tensile strength steel with low yield ratio by various welding methods such as semi-automatic CO_2 arc welding, submerged arc welding and electroslag welding, the tension tests, Charpy impact tests and hardness tests are carried out. From a series of experiments, the basic data concerning the weldability and joint performances of this new steel are obtained and the appropriate welding condition of this steel is confirmed.

1 INTRODUCTION

An application of high strength steel has advantages of saving welding cost and weight of steel and giving flexibilities to the living space by introducing new technique into structural design.

Conventional 590 MPa class tensile strength steel, however, has been scarcely applied to steel-frame buildings due to their higher yield ratio (yield point / tensile strength) and higher carbon equivalent (Ceq) compared with 490 MPa class tensile strength steel.

Decrease of yield ratio and increase of weldability are effective procedure for seismic design. In the ultimate limit state design, sufficient plastic deformable ability should be guaranteed. This point is important for seismic design of structures.

For high-rise buildings, the steel plates seem to vary in their maximum thicknesses from 50mm to 100mm. For the conventional heavy gauge high strength steel plates, it is necessary to increase carbon equivalent (Ceq=0.41~0.45%) and cracking parameter of materials (PCM=0.24~0.28%) in order to raise their tensile strength. This causes various kinds of problem in welds.

Ceq is one of indicator which gives the degree of bad influence in the weld heat-affected zone (HAZ) of welds. This is calculated to convert this influence of some elements except carbon to carbon quantity equivalently. In general, Ceq of the steel becomes higher when the steel becomes stronger, thus the metal in the HAZ is easy to harden in welds of high tensile strength steel and welds crack if welding condition is not suitable for the welds. PCM is similar indicator. There is much possibility of weld cracking in steel of higher PCM value than lower one.

The problems in welds are as follows:

1. Hardening in welds

Hardening in welds varies due to chemical composition of steel and cooling speed of welds after welding. It is remarkable in case of rapid cooling in welds and this causes weld cracking. Accordingly, it is necessary to justify heat input and to preheat in order to justify cooling speed of welds.

2. Softening in the HAZ

Microstructure in the HAZ of welds of thermal refining steel with heat treatment such as quenching and tempering transforms due to heating of welding. And then softening occurs there. The strength of this zone becomes lower than that of the base metal. It is impossible of this steel to use for welded structures if the strength of the HAZ is lower than that of the base metal.

3. Deterioration of toughness in the weld junction

The toughness in weld junction between the deposited metal and the HAZ deteriorates, because the grain size of the metal of the weld junction becomes coarser. This phenomenon becomes remarkable as the quantity of heat input increases.

The 590 MPa class tensile strength steel with lower yield ratio has been developed to solve the problem mentioned above. This steel is produced by intercritical quenchning and tempering process from $\alpha+\gamma$ phases.

By using this process, 590 MPa class strength steel plates with less than 80% yield ratio can be produced even if the Ceq and PCM value are almost equal to one of conventional 490 MPa class steel plates for welded structures. This steel is called high quality steel.

The objective of this paper is to investigate the weldability of this high quality steel for seismic resistant welded structures by examining the mechanical properties of full penetration welds of 590 MPa class tensile strength steel with low yield ratio by various welding methods and finding the appropriate welding condition of various welding methods in taking notes of strength of the joints and hardening, softening and brittleness in welds.

2 TESTED STEEL

Ceq and P_{CM} value of tested high quality steel in this study are 0.41%~0.44%, 0.20%~0.26%, respectively. And the plate thicknesses are 25mm and 50mm. Figure 1. shows the chemical composition of this steel in accordance with JIS G 0321.

Table 1. Chemical composition of high quality steel.

C	Si	Mn	P	S	Ceq	PCM
0.08	0.45	1.36	0.008	0.003	0.42	0.20
0.12	0.24	1.45	0.007	0.002	0.44	0.23
0.16	0.44	1.37	0.015	0.004	0.41	0.26
Cu	**Ni**	**Cr**	**Mo**	**V**	**Ceq**	**PCM**
0.01	0.17	0.06	0.33	0.037	0.42	0.20
0.21	0.21	0.07	0.18	0.043	0.44	0.23
0.28	0.17	tr	tr	tr	0.41	0.26

$$Ceq\,(\%) = C + \frac{Mn}{6} + \frac{Si}{24} + \frac{Ni}{40} + \frac{Cr}{5} + \frac{Mo}{4} + \frac{V}{14}$$

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

3 WELDABILITY TEST

3.1 Testing method

Table 2. shows the testing items and methods of weldability test of the material. Welding method in maximum hardness test in the HAZ and Y-groove cracking test are manual welding and semi-automatic CO_2 arc welding.
Table 3. shows the welding condition of each welding method.

Table 2. Testing items and methods.

Testing items	Methods
Tensile test	JISZ2241
Test pieces for tensile test	JISZ2201 No.5 test piece
Maximum hardness in the HAZ	JISZ3101
Y-groove Cracking test	JISZ3158

Table 3. Welding condition.

Welding process	Manual welding	CO2 arc welding
Welding consumables	LB62,4.0mm ϕ	MG601.2mm ϕ
Welding voltage and current	22~25V 170 A	30V 240~280 A
Welding speed	15 cm/min	25~30 cm/min
Heat input	17 kJ/cm	17 kJ/cm
Preheating temperature	R.T. (25),50,75, 100,125,150°C	R.T. (25),50,75, 100,125,150°C
Atmospheric temperature	25°C	25°C
Relative humidity	60%	60%

3.2 Result and discussions

3.2.1 Tensile test of base metal

Figure 1. shows the result of tensile test of base metal. The result shows base metal of each P_{CM} level satisfies yield point, tensile strength and yield ratio which are proposed as the specification of high quality steel.

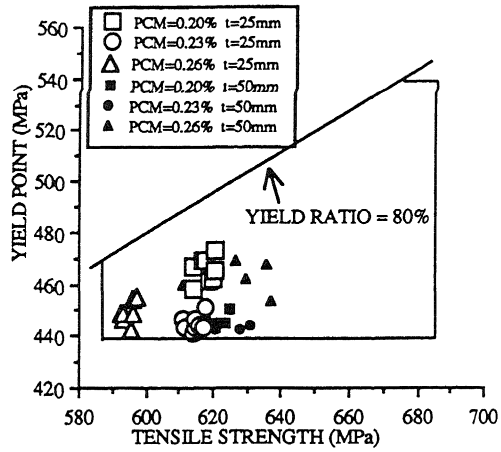

Fig. 1. Result of tensile strength test of base metal.

3.2.2 Maximum hardness in the HAZ

Figure 2. shows maximum Vickers hardness in the HAZ of high quality steel plates of 25mm and 50mm in thickness with three P_{CM} levels due to differences of welding methods and preheating temperatures.

These results indicate as follows:

1. Maximum hardness in the HAZ by manual welding *is 30~50 (Hv10) larger than by CO_2 arc welding* because of the difference of the cooling speeds between manual welding and CO_2 arc welding.
2. As the P_{CM} level of steel plates becomes higher, maximum hardness in the HAZ increases. Maximum hardness in the HAZ of the plates of P_{CM}=0.26% is about 100 (Hv10) larger than that of P_{CM}=0.20%.
3. As the preheating temperature of the steel plates becomes higher, maximum hardness in the HAZ decreases gradually. Maximum hardness in the HAZ of the plates preheated at 150°C is 30~50 (Hv10) smaller than with non-preheating (R.T.=25°C).
4. The difference of maximum hardness in the HAZ due to plate thicknesses is small in this test. The reason is that the cooling speed between t=25mm and t=50mm is not different so much in welding by small heat input such as 17kJ/cm.

3.2.3 Oblique Y-groove weld cracking test

Oblique Y-groove weld cracking test is carried out with six preheating temperatures of RT(25°C)~150°C, cracking ratios of surface crack, root crack and section crack are calculated. Figure 3. shows minimum preheating temperature for prevention of weld cracking (not to occur former three kinds of cracking) with three P_{CM} levels. The result indicates as follows:

1. In CO_2 welding, weld cracking does not occur in all P_{CM} levels and all preheating temperatures.
2. In manual welding, preheating is not needed against prevention of weld cracking in case of P_{CM}= 0.20%. In P_{CM}=0.23%, weld cracking does not occur when plates are preheated over 75°C including.
3. Also, minimum preheating temperature becomes lower as P_{CM} level becomes lower in both plate thicknesses.

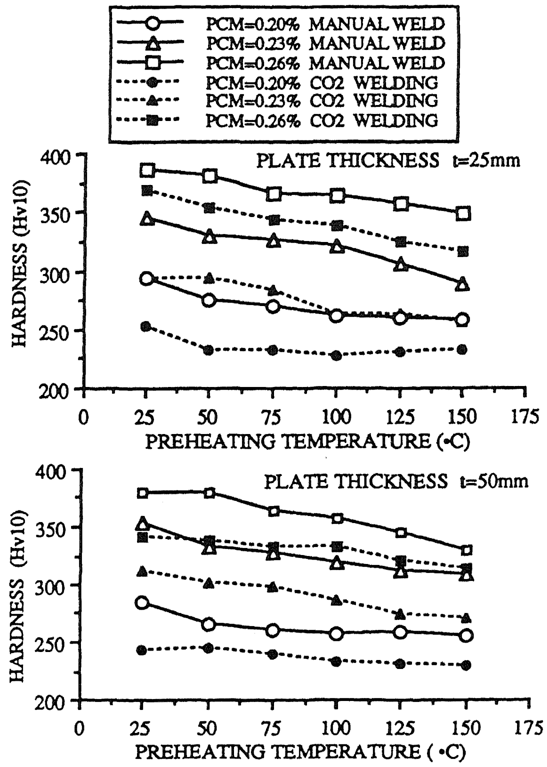

Fig. 2. Result of maximum hardness test of welds.

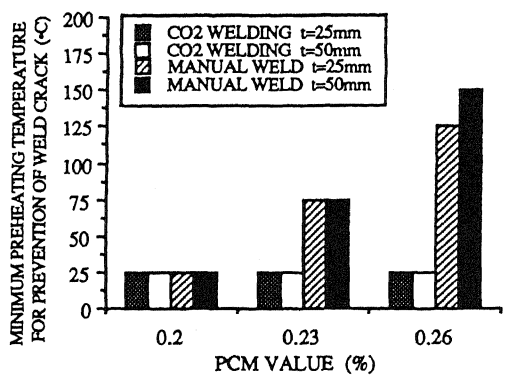

Fig. 3. Minimum preheating temperature for prevention of weld crack.

4 TEST OF JOINT WELDING

Authors believe that high quality steel is applied in mainly column and partly beam and brace. Therefore, we select corner joint (Submerged arc welding [SAW]), joint between flange of beam and diaphragm (electroslag welding [ESW]) and beam to beam or column to column joint (semi-automatic CO_2 welding [CO_2]) as the weld joint to be tested, and tests of butt joint and cruciform joint are carried out. Welding methods of butt joint are CO_2 and SAW. And that of cruciform joint are CO_2 and ESW.

4.1 Testing method

4.1.1 Butt joint

Parameters of the test are plate thickness (t=25,50mm), PCM level (PCM=0.20,0.23,0.26%), welding method (CO_2, SAW), heat input of SAW (200,400 kJ/cm) and interpass temperature of CO_2 (I.P.T.=150,300°C,free).
Table 4. shows the list of the test pieces of one side welding of butt joint and the welding condition. And table 5. shows the testing items and methods. Positions for taking the test pieces of Charpy impact test in direction of thickness are 1/4t from surface of the steel plate of 25mm, and 1/2t from surface of the steel plate of 50mm. Positions of the noch are the center of the deposited metal, weld junction (bond), bond+1mm, +3mm ,+5mm and base metal. The testing temperature of the test is 0°C. Charpy absorbed energy is obtained.
Positions for measuring of hardness test in direction of thickness is 1/2t from surface of steel plates of 25, 50mm in welds by CO_2 and SAW.

4.1.2 Cruciform joint

Testing parameter of the test are the thickness (t=25,50mm) and PCM level (PCM=0.20,0.23,0.26%). The welding condition and the test piece of cruciform joint is shown in table 6. and figure 4.. The testing items and methods are the same as the test of butt joint.

4.2 Result and discussion

4.2.1 Weld joint tensile test

Table 7. and 8. show the results of welded joint tensile strength test of butt joint and cruciform joint, respectively.
These results indicate as follows:
1. All test pieces of both butt joint and cruciform joint by CO_2 fracture in base metal and satisfy the tensile strength and elongation of the specification of high quality steel within the welding condition of this test.
2. Every test piece of butt joint by SAW satisfies the tensile strength of the specification of high quality steel, though the test pieces of 400 kJ/cm heat input of welds which plate thickness is 25mm and PCM=0.26% and which plate thickness is 50mm and PCM=0.23% and 0.26% fracture in the HAZ or the deposited metal.
3. The test pieces of cruciform joint by ESW of PCM=0.20% and 0.23% fracture in base metal and satisfy the specification of tensile strength of high quality steel (590MPa). But those of PCM=0.26% fracture in the deposited metal or the HAZ of welds.

4.2.2 Charpy impact test of welded joint

Figure 5. shows the result of Charpy impact test of butt joint. Plate thickness is 25mm, and welding method are CO2 and SAW. Charpy absorbed of the deposited metal and the HAZ, which are the bond and the bond+1mm, is smaller than the base metal. But it increases gradually as the distance between the tested position and the deposited metal becomes larger. Though Charpy absorbed energy of the deposited metal of PCM=0.26% indicates relatively low value, the result of the welds by SAW is almost the same.

Table 4. Test piece of one side welding of butt joint and welding condition.

Plate thickness t (mm)	PCM value (%)	Welding method	Heat input kJ/cm	Interpass temp. (°C)	Groove	preheating temp. (°C)	Welding consumables
25	0.20	CO2	24	150			
	0.20	CO2	24	300	Singlebevel	80 ~ 100	JISZ3312 YGW-21
	0.20	CO2	24	Free			
	0.20	SAW	200	-	Single V	-	JISZ3183 S-584
	0.23	CO2	24	150			
	0.23	CO2	24	300	Singlebevel	80 ~ 100	JISZ3312 YGW-21
	0.23	CO2	24	Free			
	0.23	SAW	200	-	Single V	-	JISZ3183 S-584
	0.26	CO2	24	150			
	0.26	CO2	24	300	Singlebevel	80 ~ 100	JISZ3312 YGW-21
	0.26	CO2	24	Free			
	0.26	SAW	200	-	Single V	-	JISZ3183 S-584
50	0.20	SAW	200	Less than 150	Single V		JISZ3183 S-584
	0.20	SAW	400	Less than 150			
	0.23	SAW	200	Less than 150	Single V	-	JISZ3183 S-584
	0.23	SAW	400	Less than 150			
	0.26	SAW	200	Less than 150	Single V		JISZ3183 S-584
	0.26	SAW	400	Less than 150			

Table 5. Testing items and methods of joint welding.

Test name	Testing methods	Test pieces
Welded joint tensile test	JISZ2241	Width x Length = 2t x 6t
Charpy impact test	JISZ2242	JISZ2202 No.4 test piece
Hardness test	JISZ2244 Hv10	-

Table 6. Welding conditions of cruciform joint.

	CO2	ESW
Plate thickness t	25, 50 mm	25, 50 mm
PCM value (%)	0.20,0.23,0.26	0.20,0.23,0.26
Heat input (kJ/cm)	24	400[t=25mm] 800[t=50mm]
Welding consumables	JISZ3312 YGW21	YM•36E1.6φ, YF•15 nozzle 12f
Preheating temp.	80~100	-
Interpass temp.	300	-

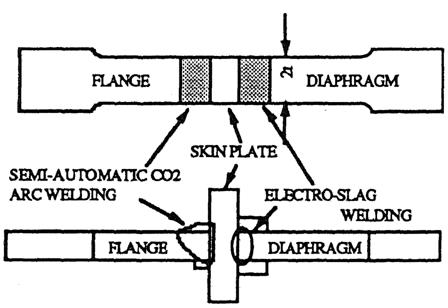

Fig. 4 Test piece of cruciform joint.

Figure 6. shows the result of Charpy impact test of welds by SAW in case of changing heat input. Charpy absorbed energy of the weld of 200kJ/cm heat input more than 60~70J. Though Charpy absorbed energy decreases in the HAZ in case of 400kJ/cm heat input, it is more than 20J.

Figure 7. and 8. shows the result of cruciform joint by CO_2 and ESW,respectively. In CO_2, deterioration of Charpy absorbed energy is not remarkable. On the other hand, in ESW, it is relatively large in the bond and the HAZ in welds. The degree and area of the decrease become large when heat input becomes large and when PCM level becomes lower.

4.2.3 Hardness test

Figure 9. shows one of the results of hardness test of cruciform joint (t=25mm, PCM=0.20%). The inspected position in direction of thickness is 1/2t from surface. Common tendency of hardness of butt joint and cruciform joint in all PCM levels and welding methods is that there are hardening from the weld junction to the deposited metal and softening in the HAZ.

Figure 10. shows the relation between PCM level of the steel plate and maximum and minimum hardness of.the welds. This result indicates that the degree of the hardening and softening is within the range of ±50 Hv. This is supposed considerably narrow range compared with conventional 490 MPa class tensile strength steel, and weld crack scarcely occurs within this range of Vickers hardness. And the metal in the HAZ has sufficient ability of elongation. In the steel plate of 25mm in thickness, the maximum hardness of welds by CO_2 is smaller than welds by SAW. In the welds of the steel plate of 50mm in thickness by SAW, the range of hardness of welding of 400 kJ/cm heat input is narrower than that of 200 kJ/cm heat input. The reason is supposed that welds of 400 kJ/cm heat input are given equational heat affect from the base metal to the deposited metal including, therefore the cooling speed in the weld junction slows down.

Figure 10. shows the result of Vickers hardness test of cruciform joint. The hardening and the softening in the welds by CO_2 and ESW are small. And they become smaller when PCM level becomes lower. The maximum hardness in the test of welded joint is smaller than that of the weldability test. The reason is supposed that the cooling speed of the welded joint is slowed down than that of the weldability test.

Table 7. Testing result of weld joint tensile test of butt joint.

Plate thickness t (mm)	PCM value (%)	Welding method	Heat input kJ/cm	Interpass temp. (°C)	Tensile strength (MPa)	Elongation (%)	Fracture portion
25	0.20	CO2	24	150	614	31.6	Base metal
	0.20	CO2	24	300	612	31.3	Base metal
	0.20	CO2	24	Free	607	30.7	Base metal
	0.20	SAW	200	-	599	26.5	Base metal
	0.23	CO2	24	150	605	30.7	Base metal
	0.23	CO2	24	300	596	30.5	Base metal
	0.23	CO2	24	Free	607	31.8	Base metal
	0.23	SAW	200	-	607	28.0	Base metal
	0.26	CO2	24	150	633	27.4	Base metal
	0.26	CO2	24	300	621	27.8	Base metal
	0.26	CO2	24	Free	639	27.0	Base metal
	0.26	SAW	200	-	604	22.6	Heat-affected Zone
50	0.20	SAW	200	Less than 150	599	27.1	Base metal
	0.20	SAW	400	Less than 150	593	23.2	Base metal
	0.23	SAW	200	Less than 150	616	27.9	Base metal
	0.23	SAW	400	Less than 150	609	22.5	Deposited metal
	0.26	SAW	200	Less than 150	601	26.9	Base metal
	0.26	SAW	400	Less than 150	596	17.2	Deposited metal

Table 8. Result of weld joint tensile test of cruciform joint.

Plate thickness t (mm)	PCM value (%)	Welding method	Tensile strength (MPa)	Fracture portion
25	0.20	CO2	606	Base metal
		ESW	598	Base metal
	0.23	CO2	606	Base metal
		ESW	604	Base metal
	0.26	CO2	634	Base metal
		ESW	597	HAZ
50	0.20	CO2	607	Base metal
		ESW	589	Base metal
	0.23	CO2	619	Base metal
		ESW	604	Base metal
	0.26	CO2	604	Base metal
		ESW	573	Deposited metal

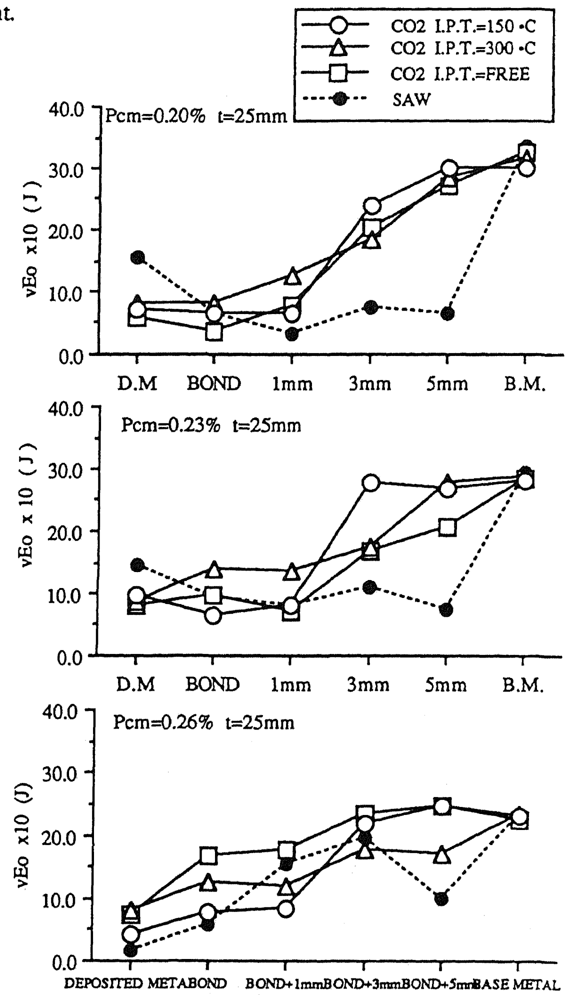

Fig. 5. Results of Charpy impact test of butt joint (t=25mm CO2 and SAW).

5. CONCLUSIONS

A series of tests are carried out with 590 MPa class strength steel with low yield ratio (high quality steel) of three kinds of PCM levels and of 25mm and 50mm in thickness by manual welding, semi-automatic CO2 welding, submerged arc welding and electroslag welding. The conclusions of this study can be summarized as follows:

1. In manual welding, the risk of weld cracking of steel plate under 0.23% including in PCM level is negligibly small even if the steel plate is not preheated.
2. In semi-automatic CO2 welding, the performance of the welded joint of the steel plate under 0.23% including in PCM level is satisfactory even if the steel plate is not preheated.
3. In the large heat input welding such as submerged welding and electroslag welding, the performance of the welded joint is satisfactory when PCM level of the steel is not more than 0.23%. But the upper limit of heat input is supposed to be 800 kJ/cm of the steel plate of 50mm in thickness according to Charpy impact test.
4. The tensile strength of he welded joint of high quality steel equals the tensile strength of the base metal within the welding condition in the present study, and it is possible to be applied to the high tensile strength steel for welded structure.

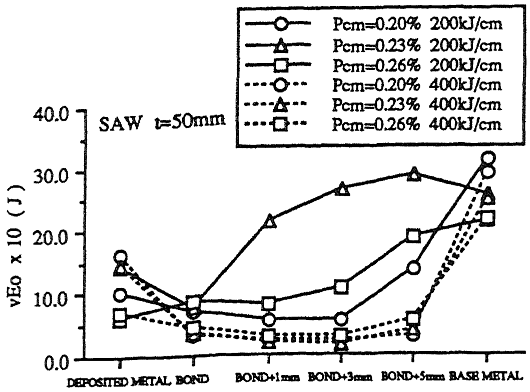

Fig. 6 . Result of charpy impact test (SAW t=50mm) .

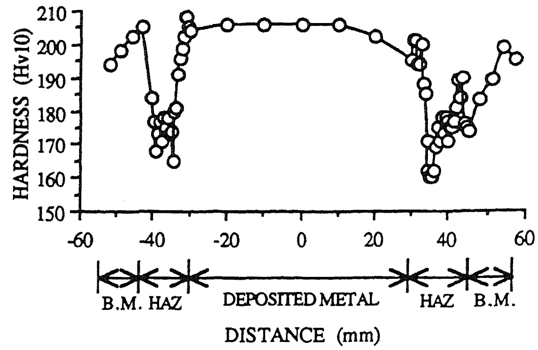

Fig. 9. Result of hardness test (cruciform joint Pcm=0.20% t=25mm SAW).

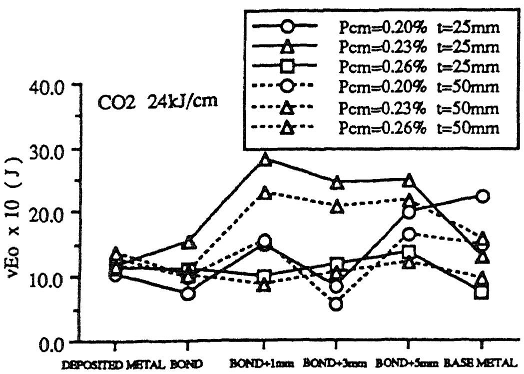

Fig. 7. Result of charpy impact test (cruciform joint).

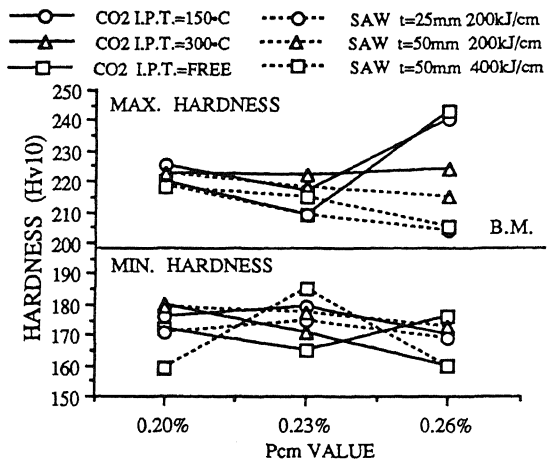

Fig. 10. Rsult of hardness test of butt joint.

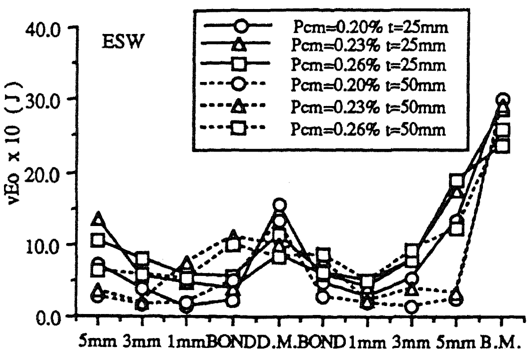

Fig. 8. Result of Charpy impact test of cruciform joint (ESW t=25,50mm).

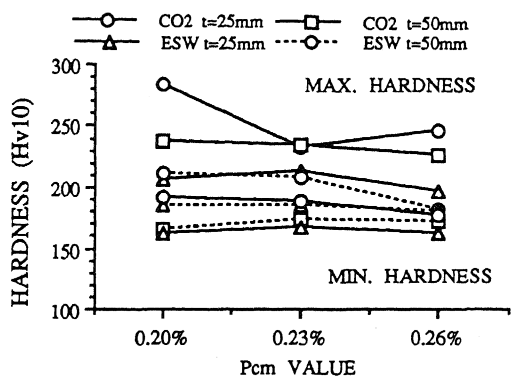

Fig. 11. Result of hardness test of cruciform joint.

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