Mechanical Properties on Electron Beam Welds of Constructional High Tension Steels (Report V)†

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Abstract

The effects of welding condition and chemical composition on the occurring characteristics of weld porosities were studied in this investigation by using twenty different constructional steels of 40 to 80 Kg/mm² in strength. The remarkable conclusion are as follows.

(1) *The bead shape changes from wedge shaped-type to wine cup shaped-type with an increase of a_b parameter, and the penetration depth becomes to be maximum at a_b: 0.9.*

(2) *The weld defect of porosities occurred in weld metal were roughly divided into two classes, that is "Root porosity" in the bottom of weld penetration and "A-porosity" in the middle part of weld penetration.*

(3) *The amount of A-porosity occurred is the most in case of a_b: 1.1. Meanwhile Root-porosity is decreased with an increase of a_b parameter.*

(4) *A-porosity tends to be decreased with an increase of weld heat input and it is increased with an increase of nitrogen or oxygen content in steel.*

(5) *Concerning to the occurring of weld porosities the allowable limit in quantity for nitrogen and oxygen contents in steel is less than about 60 and 70ppm in case of 15KJ/cm weld haet input, respectively, and in general it is raised with an increase of weld heat input.*

(6) *In general the impact strength of the weld metal is irrespective of the variation of weld heat input within a limit of this investigation. Furthermore the impact strengths for most of weld metal are satisfied with maximum value prescribed by JIS or WES Specification, with the exception of some of HT60 and 80 weld metals.*

1. Introduction

The aim of this series of investigation is to make clear the various characteristics of electron-beam welds for some commercial high tension steels (HT50, HT60 and HT80). The authors studied on the mechanical properties of electron-beam welds such as hardness distribution, tensile-, bend-, impact- and fatigue-properties in the two previous reports.[1), 2)] It was found that these electron-beam welds of high tension steels would be almost satisfied with practical use according to the results of these mechanical tests. The authors treated about the particular behavior of impact properties for electron-beam weld metal, which were characterized by hardened weld zone and narrow bead width as compared with those of welds by conventional arc welding method in the two previous reports.[3), 4)] That is, the detailed examinations were systematically done concerning the behavior on the transition temperature for fracture mode (Trm) in the impact test of electron-beam weld metal.

Then in this report the authors have firstly investigated the relation between welding conditions and weld porosities by using four types of representative constructional steel (SS41, HT50, 60 and 80, the minimum strength of which are 41, 50, 60 and 80Kg/mm² respectively) in detail. Nextly, the effect of chemical compositions in constructional steels on weld porosities has been investigated by using the twenty different constructional steels from 40 to 80Kg/mm² in strength. Moreover the impact properties in the welds of these steels were also investigated and compared.

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2. Experimental Procedure

2.1 Materials used

The materials used in this investigation are twenty different commercial constructional steels, which are composed by four types of SS41, three types of SM41, two types of atmospheric corrosion resistant steel (SMA41 and SMA50), four types of HT50, four types of HT60 and three types of HT80 steels. The respective steel mark is classified by Japan Industrial Standard Specification (JIS Specification), and the number represents the minimum strength in tensile strength. The chemical compositions of these twenty different steels are listed in Table 1. The variation range of chemical composition in these steels is as follows —— C: 0.12% to 0.22%, Si: 0.03% to 0.48%, Mn: 0.68% to 1.46%, O: 15ppm to 420ppm, N: 29ppm to 100ppm. The carbon equivalent (C_{eq}) of these steels changes from 0.25 to 0.53. Moreover all of these steels are 25mm in plate thickness. The material sign is indicated as S for SS41, M for SM41, R for SMA41 or SMA50, X for HT50, Y for HT60 and Z for HT80 steel. All of HT60 and 80 steels shown in Table 1 are quenched and tempered materials, and the others are not heat-treated. The dimension of each test plate for electron-beam welding is 150mm in width and 500mm in length.

2.2 Welding condition and experimental method

High vacuum type-electron-beam welder, the maximum beam power of which is 15KW (30KV-500mA) is employed in this investigation. Welding for all materials was performed with one pass bead-on-plate method. Any oxide film and scale on plate surfaces was completely machined along welding direction. Furthermore all of test plates were completely de-magnetized, and also plate surfaces of them were made clean with degreasing regent in advance of electron-beam welding.

The relation between welding condition and the occurring characteristics of weld porosities is firstly investigated by using four representative materials in Table 1, that is to say, SS41 (S1), HT50 (X1), HT60 (Y1) and HT80 (Z1) steels. Table 2 shows the welding conditions adopted in this experiment. That is, two weld heat inputs of 15 and 30KJ/cm were selected, and moreover a_b parameter (D_O/D_F, D_O: Objective distance, D_F: Focal length) is varied for the various six levels to the respective weld heat input. The focal length (D_F) for the beam power of 9KW (30KV-300mA) was recognized to be 257mm from the preliminary test of slope-welding method.[5] Furthermore the penetration depth in 30KJ/cm weld heat input was often observed to be more than 25mm plate thickness, in case of which the welding

Table 1 Chemical compositions of materials used.

(Wt%)

Composition / Steel	Sign	C	Si	Mn	P	S	Cu	Ni	Cr	Mo	V	O (ppm)	N (ppm)	Ceq*
SS-41	S1	0.13	0.21	0.69	0.017	0.012	–	–	–	–	–	20	47	0.25
	S2	0.22	0.03	0.98	0.014	0.024	–	–	–	–	–	45	55	0.38
	S3	0.20	0.04	0.87	0.017	0.020	–	–	–	–	–	155	31	0.35
	S4	0.19	0.06	0.96	0.012	0.020	–	–	–	–	–	85	37	0.35
SM-41	M1	0.17	0.22	0.76	0.018	0.017	–	–	–	–	–	30	53	0.31
	M2	0.16	0.25	0.97	0.016	0.010	–	–	–	–	–	15	48	0.33
	M3	0.18	0.14	0.75	0.024	0.017	–	–	–	–	–	30	38	0.31
SMA-41A	R1	0.17	0.06	0.68	0.009	0.018	0.21	tr.	0.36	0.006	–	420	43	0.36
SMA-50B	R2	0.16	0.36	1.06	0.017	0.009	0.31	tr.	0.31	0.006	–	30	79	0.42
HT-50 SM-50B	X1	0.16	0.47	1.39	0.017	0.015	–	–	–	–	–	20	31	0.41
	X3	0.16	0.35	1.41	0.019	0.019	–	–	–	–	–	20	73	0.41
HT-50 SM-50A	X4	0.18	0.48	1.42	0.014	0.005	–	–	–	–	–	65	51	0.44
	X5	0.18	0.42	1.45	0.018	0.010	–	–	–	–	–	25	35	0.44
HT-60	Y1	0.14	0.31	1.28	0.015	0.015	–	–	–	–	–	30	49	0.37
	Y2	0.15	0.37	1.46	0.017	0.015	–	–	0.03	–	0.03	35	29	0.42
	Y3	0.12	0.23	1.24	0.016	0.007	0.13	–	–	–	–	25	41	0.35
	Y4	0.12	0.28	1.34	0.016	0.007	0.01	0.07	0.03	0.010	0.04	35	56	0.37
HT-80	Z1	0.13	0.30	0.86	0.013	0.004	0.22	0.87	0.52	0.42	0.04	20	54	0.52
	Z3	0.14	0.30	0.79	0.017	0.006	0.22	0.83	0.46	0.42	0.04	45	100	0.51
	Z4	0.14	0.26	1.10	0.015	0.007	0.02	0.02	0.61	0.29	0.03	30	69	0.53

* $Ceq = C + \frac{1}{6}Mn + \frac{1}{24}Si + \frac{1}{40}Ni + \frac{1}{5}Cr + \frac{1}{4}Mo + \frac{1}{14}V$ (JISG3106)

Table 2 Welding conditions in various a_b parameters.

Beam power (KV-mA)	Welding speed (cm/min.)	Weld heat input (KJ/cm)	a_b parameter (Do/D_F)
30-300 (9KW)	36	15	0.75, 0.9, 1.0 1.1, 1.2, 1.4
30-300 (9KW)	18	30	

was performed by means of the stacking of two plates.

Nextly, the examination was done concerning the effect of chemical compositions on the occurring characteristics of weld porosities by using twenty different steels. In this experiment the welding for these steels was done with a_b parameter: 1.1 for the respective weld heat input in Table 2, as in the first experiment there is the most numerous porosities in the weld metal in case of a_b: 1.1. The existence of weld porosities was examined by means of X-ray film inspection for all of welds referring to Japan Industrial Standard Specification (JIS Z 3104-1968). Evaluation for the amount of weld porosities was done with the X-ray film which passed through the general grade for JIS Specification. Moreover all of welds for these steels were inspected by irradiation of X-ray not only to vertical but also to lateral directions to the weld metal. In order to investigate the location of porosities which occurred in the different depth of the deep penetrated weld metal, it should be better to inspect from lateral direction. For this purpose each specimen was machined longitudinally along the welding direction for both sides of the weld metal in 10mm width.

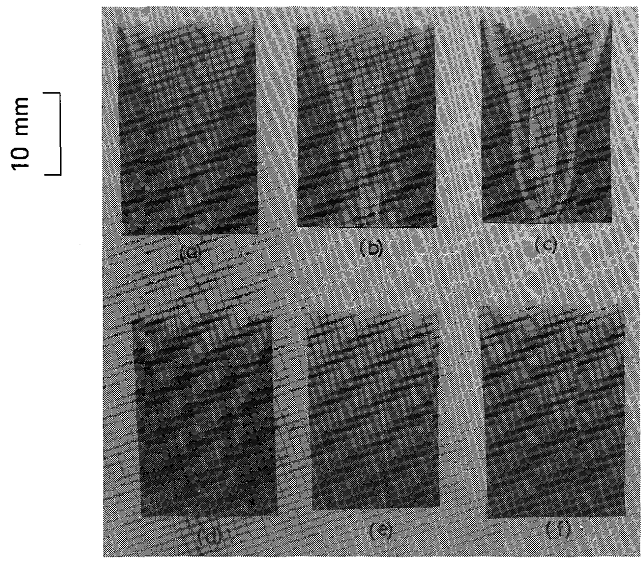

Fig. 1 Macro-phtographs for cross-sectional HT80 welds of 30KJ/cm weld heat input in various a_b parameters.
(a) a_b=0.75 (b) 0.9 (c) 1.0 (d) 1.1
(e) 1.2 (f) 1.4

Moreover the impact test was performed with standard Charpy 2mm V-notch specimens concerning the welds of twenty different steels. All of Charpy test specimens were notched at the center of weld metal, and machined from 3mm under the plate surface.

3. Bead Shape and Hardness

Fig. 1 shows the macro-photographs for cross sectional HT80 welds of 30KJ/cm weld heat input in various a_b parameters as an example. With an increase of

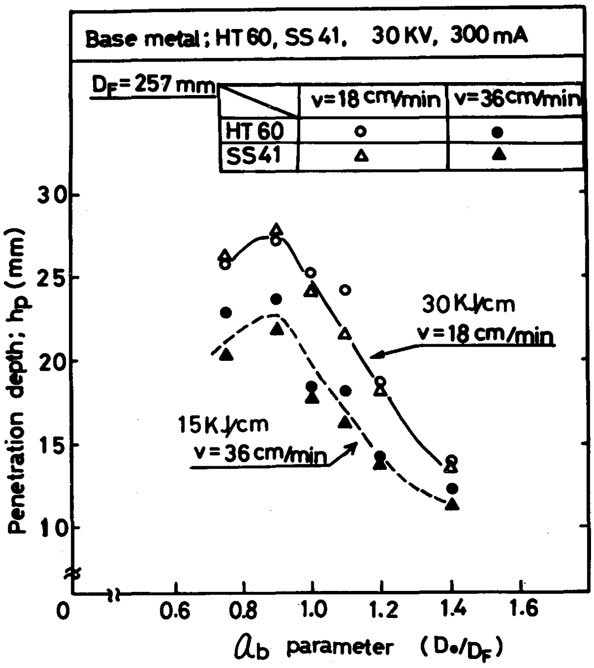

Fig. 2 Relation between a_b parameter and penetration depth in 15 and 30KJ/cm weld heat inputs.

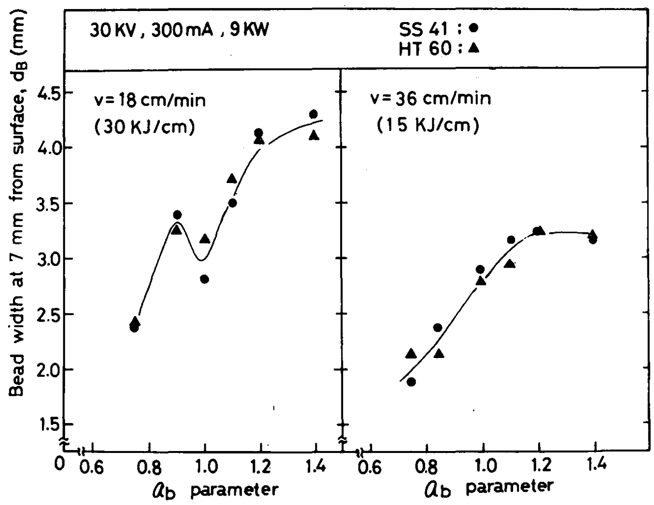

Fig. 3 Relation between a_b parameter and bead width in 15 and 30KJ/cm weld heat inputs.

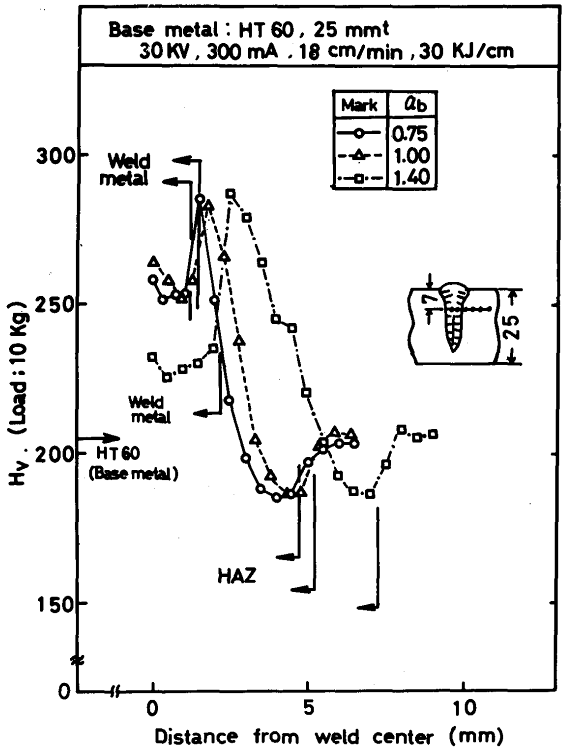

Fig. 4 Vickers hardness distributions of HT60 welds in 30KJ/cm weld heat input for various a_b parameters.

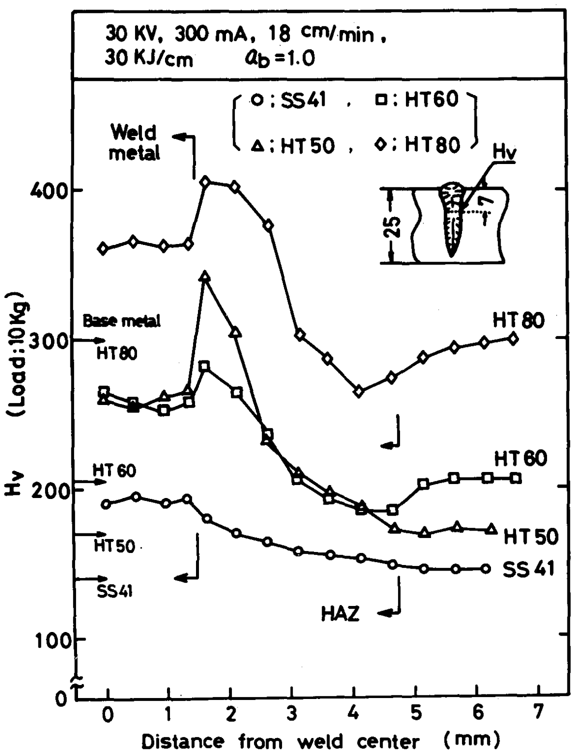

Fig. 5 Vickers hardness distributions for welds of four representative steels in case of 30KJ/cm weld heat input.

a_b parameter, the bead shape gradually tended to change from wedge-shaped type to wine cup-shaped type. The penetration depth was about 27mm in maximum at a_b parameter: 0.9.

Besides, the bead shapes of 15KJ/cm weld heat input similarly changed to be smaller as compared with those of 30KJ/cm weld heat input. Fig. 2 shows the relation between a_b parameter and penetration depth in 15 and 30KJ/cm weld heat inputs for SS41 and HT60 weld metals. The penetration depth is irrespective of the difference in materials and it is also maximum at a_b: 0.9 for the respective weld heat input. Fig. 3 shows the variation of the bead width at 7mm depth from plate surface in various a_b parameters, however it didn't show the continuous variation at a_b: 1.0 in case of 30KJ/cm weld heat input. It was caused by a little change of bead shape, that is to say, the bead at a_b: 1.0 had the constricted part just at about 7mm depth from plate surface as shown in Fig. 1 (c).

Fig. 4 shows an example of Vickers hardness distribution for HT60 welds of 30KJ/cm weld heat input in three different a_b parameters. The hardness of welds was measured by using Vickers hardness tester with 10Kg load. The measured location for the welds was at 7mm inward depth from plate surface. The softened zone was observed in each distribution curve because HT60 was the heat treated steels. The hardnesses of weld metal in case of a_b: 1.4 showed a little lower value than those in the other a_b parameters, however the maximum hardness for the respective weld was observed at the HAZ near fusion boundary, the value of which showed nearly constant value (Hv≒285). Therefore the decrease of the hardness in the weld metal for a_b=1.4 seems to be mainly caused by the variation of the vaporization of Mn element in the weld metal during electron-beam welding due to the difference in size of the molten puddle. Fig. 5 shows the comparison of Vickers hardness distributions of the welds for four representative steels (S1, X1, Y1 and Z1) in case of 30KJ/cm weld heat input and 1.0 in a_b parameter. Maximum hardness in general was observed at the HAZ near fusion boundary except for SS41 welds. This seems to be related to the Mn element in SS41 steel, which is the lowest quantity among the four steels as shown in Table 1. Moreover softened zones were observed in the hardness distributions of HT60 and 80 welds because of heat-treated materials.

Fig. 6 shows the relation between a_b parameter and average hardness of weld metal (Hw) in four materials for 15 and 30KJ/cm weld heat inputs. Hw in each material was not remarkably varied to the variation of a_b parameter in general, and always showed the higher value than the hardness of respective base metal. However the

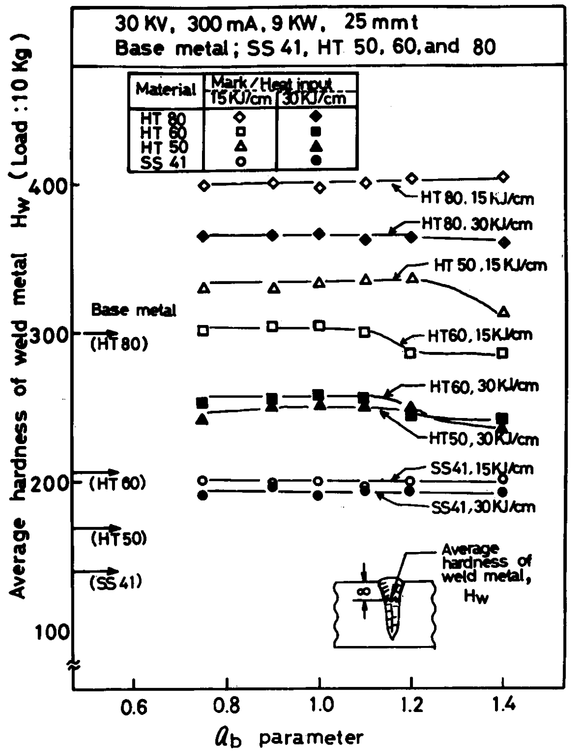

Fig. 6 Relation between a_b parameter and average hardness of weld metal (Hw) for four representative steels.

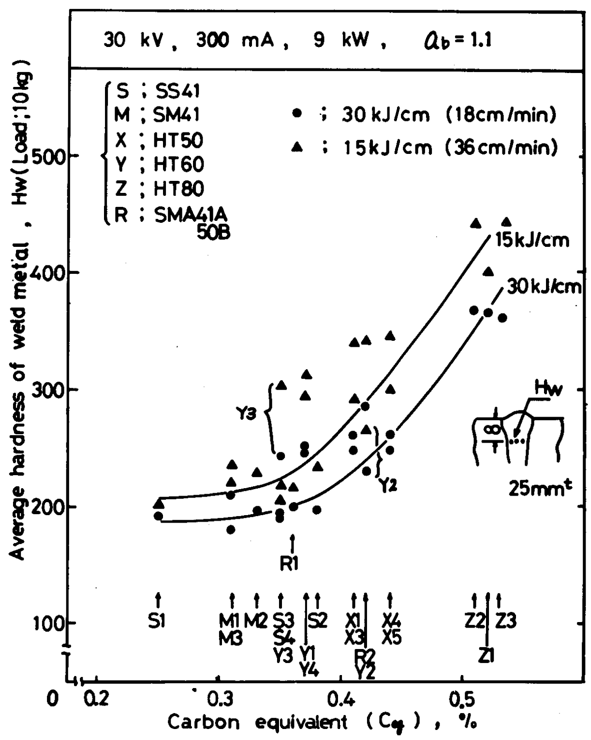

Fig. 7 Relation between carbon equivalent and average hardness of weld metal (Hw) for twenty different steels.

Hw for HT50 and 60 weld metals, the Mn quantity of which is relatively high (about more than 1.0 wt.%) among four steels has a tendency to be a little decreased with an increase of a_b parameter. The decrease of Hw is considered to be caused by the bead shape variation as above-mentioned. Namely it is resulted that the quantity of Mn element-vaporization for wine cup-shaped bead is more than that for wedge-shaped-bead due to the difference in size of the molten puddle area for fusion surface. Furthermore there is no obvious variation in the Hw of SS41 weld metal in spite of the change of weld heat input. This reason is considered to be caused by the low carbon equivalent (C_{eq}) of SS41, the value of which is 0.25, however these problems should be considered by referring to C.C.T. diagram for respective material. Fig. 7 shows the relation between the carbon equivalent (C_{eq}) designated in Table 1 and the average hardness of weld metal (Hw) in twenty different steels by using weld heat input as a parameter. The Hw in SS41 and SM41 steels, the C_{eq} of which is relatively low among twenty steels is almost irrespective of the C_{eq} for each weld heat input, while the Hw in the other materials in general tends to be increased with an increase of C_{eq}. Moreover the Hw of HT80 weld metal in 15KJ/cm weld heat input often exceeds more than 400 V.H.N.

4. Weld Metal Porosities

4.1 Relation between welding condition and weld porosities

The relation between welding condition and weld defect was studied by using four representative steels, that is, SS41 (S1), HT50 (X1), HT60 (Y1) and HT80 (Z1). As the result for X-ray inspection to the vertical direction for the weld metal of these steels, the synthetic grade for most of them is almost allowable for the first class referring to JIS Z 3104 with the exception of the SS41 for 15KJ/cm weld heat input and 1.1 in a_b parameter, the grade of which corresponds to the second class. That is, only one weld out of forty eight samples was judged to the second class for the synthetic grade. Furthermore the weld defects which were often observed in these weld metals were not crack but porosities.

Nextly the following is concerning the X-ray test results which were obtained by applying X-rays to the lateral direction for the weld metal. Namely the weld porosities which occurred to the penetrated direction for the weld metal were inspected in detail. The weld porosities occurred in weld metal were devided into two main classes, that is, Root-porosity (R-porosity) and Active zone-porosity[5] (A-porosity) which is conveniently called in this report. The former is a hole type defect

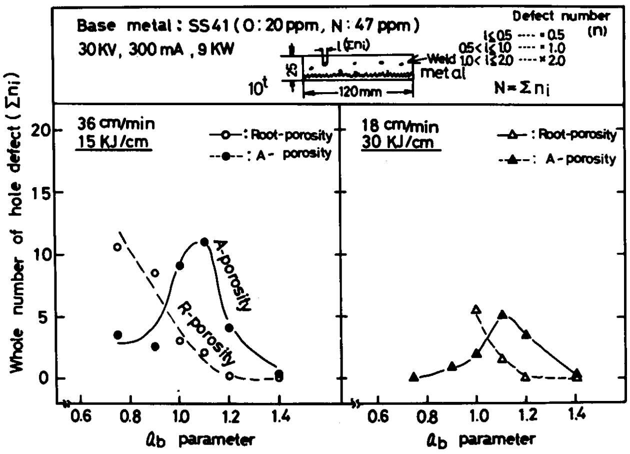

Fig. 8 Occurring characteristics of weld porosities for SS41 welds in various welding conditions.

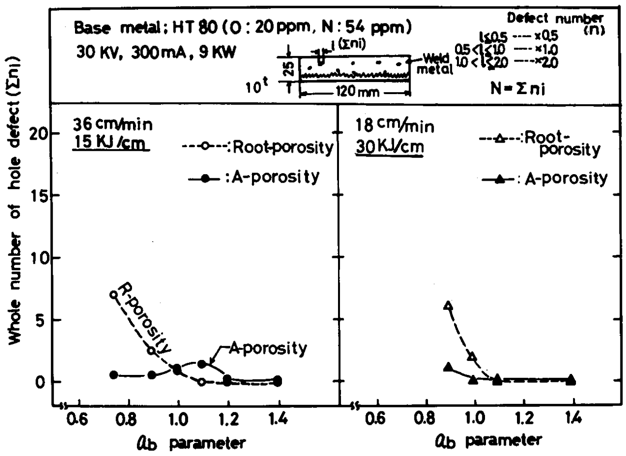

Fig. 11 Occurring characteristics of weld porosities for HT80 welds in various welding conditions.

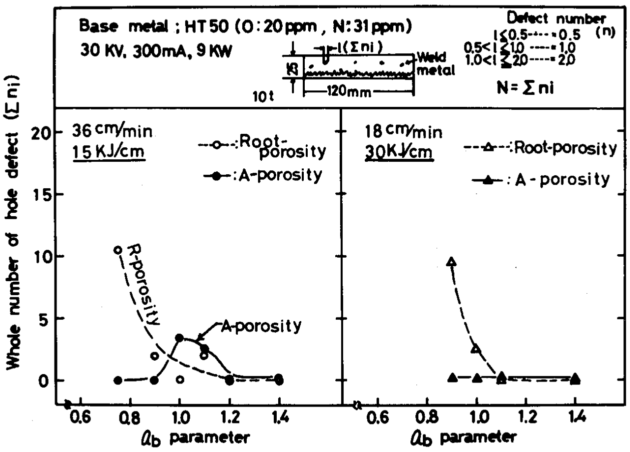

Fig. 9 Occurring characteristics of weld porosities for HT50 welds in various welding conditions.

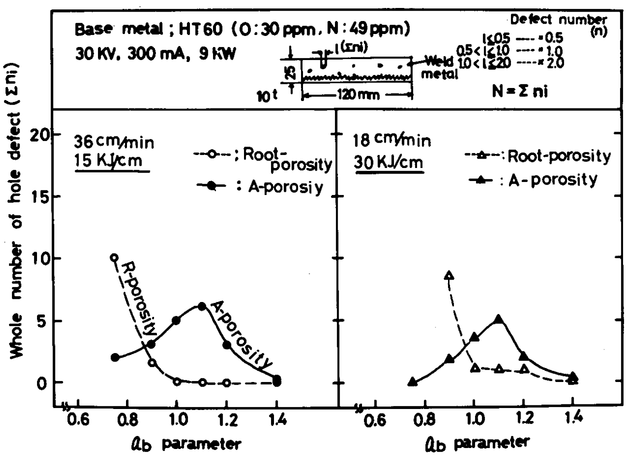

Fig. 10 Occurring characteristics of weld porosities for HT60 welds in various welding conditions.

peculiar to electron-beam welding, which occurrs in the tip of the spiking, and the latter is also a hole type defect which occurrs in the middle and upper parts in the bead penetration of weld metal. R-porosity is often observed at the weld part which corresponds to respective penetration depth, and the diameter is less than 0.5mm in size in general, while A-porosity is observed as the relatively large defect as compared with R-porosity, the diameter of which is from 0.5 to 2.0mm in size.

Fig. 8 through 11 show the occurring characteristics of R- and A- porosities in various welding conditions for SS41 (S1), HT50 (X1), HT60 (Y1) and HT80 (Z1) welds, respectively. The hole defect number (N) was calculated by the sum of the respective defect coefficient (n) prescribed for all weld porosities existed in 120mm length of the stable weld bead. The hole defect coefficient (n) is specified in accordance with the longest diameter (ℓ) for each porosity referring to JIS specification as n=0.5, 1 and 2 for ℓ≦0.5, 0.5<ℓ≦1.0 and 1.0<ℓ≦2.0 mm, respectively. Generally the hole defect number for R-porosity tends to be decreased with an increase of a_b parameter, and moreover R-porosity has a tendency to occur more numerously as the weld heat input is increased. Furthermore the amount of A-porosity occurred was the most at a_b:1.1 for respective weld heat input for all materials. This seems to be closely related to the shape of bead penetration. That is to say, as seen in Photo. 1 (c) and (d), the shape of the weld bead at a_b: 1.1 is expanded at weld bottom and also constricted under the snake-head. Therefore the A-porosity is expected to be easy to occur at this expanded part of weld bead. In general the A-porosity tends to be decreased with an increase of weld heat input, which is considered to be depended on the solidification time during welding. Further the amount of A-porosity occurred for the SS41 weld is the most among the four representative steels, while in HT80 weld it was hardly observed in any welding condition.

4.2 Relation between chemical compositions and weld porosities

As above-mentioned, A-porosity tends to occur the most numerously in case of a_b:1.1 for respective weld heat input in spite of the difference in materials. Then for the remained sixteen different steels, the bead-on-plate welding was performed with a_b:1.1 for 15 and 30KJ/cm weld heat inputs in order to study the relation between chemical composition in steel and weld porosities. Firstly, according to the results for X-ray inspection to the vertical direction to the weld metal, explosion-or huge void-type weld porosities were observed in the weld metals of SMA 41A (R1) for both 15 and 30KJ/cm weld heat inputs, and moreover in the weld metal of two types of SS41 steel (S2 and S3 materials), the void-type porosities were observed in case of 30KJ/cm weld heat input, the largest diameter of which is about 7mm to 8mm. Furthermore the synthetic grade for the weld metals of S3, R2, X3 and Z4 materials were judged to the second class in case of 15KJ/cm referring to JIS Specification, while the grade for the other weld metals were judged to the first class, that is, the number of the weld metals for the first class was twenty four out of thirty two specimens.

Nextly, the result of X-ray inspection by applying X-ray to the lateral direction for the weld is as follows. The hole defect number for the weld metal was calculated only for A-porosity existed in 120mm length of the stable bead with the exception of the R-porosity which are peculiar to electron-beam welding. Fig. 12 shows the relation between weld heat input and hole defect number (N) of A-porosity in the weld metal for twenty different steels. It is found that the hole defect number for A-porosity in general occurred in weld metal has a tendency to be decreased with an increase of weld heat input with one or two exceptions. Besides the Explosion-or void-type porosities occurred in the weld metal of the atmospheric corrosion resistant steel (SMA 41A; R1), which is expected to be due to the extremely high oxgen content (420ppm) in the steel. The illustration for explosion-or void-type porosities observed in the weld metal is shown in Fig. 13. The void-type porosities were often observed in the weld metal of 30KJ/cm weld heat input, the penetration depth of which is deeper.

Fig. 14, 15 and 16 show the relation between the hole defect number of A-porosity and the carbon, silicon

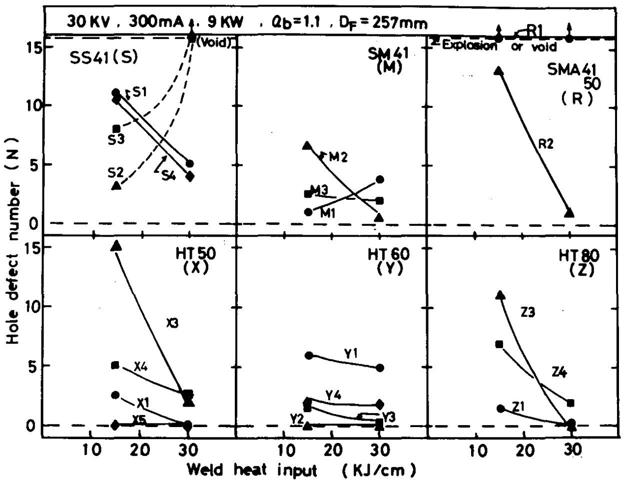

Fig. 12 Relation between weld heat input and hole defect number (N) in weld metal for various materials.

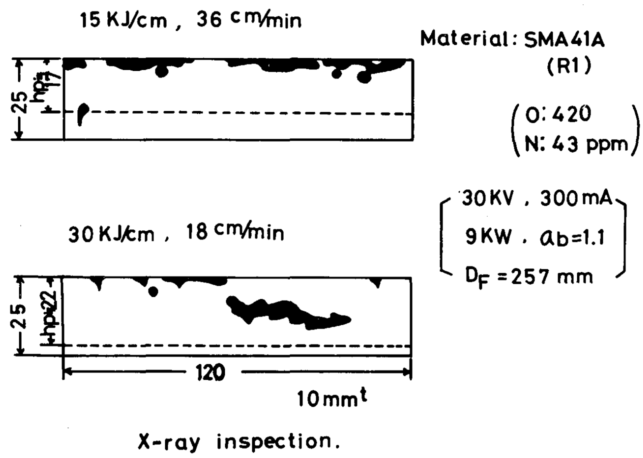

Fig. 13 Illustration for explosion- or void-type porosities observed in SMA41A (R1) welds.

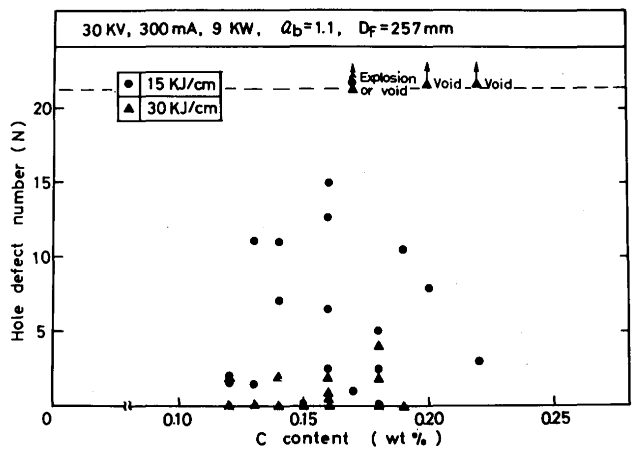

Fig. 14 Relations between carbon content and hole defect number in weld metal for twenty different steels.

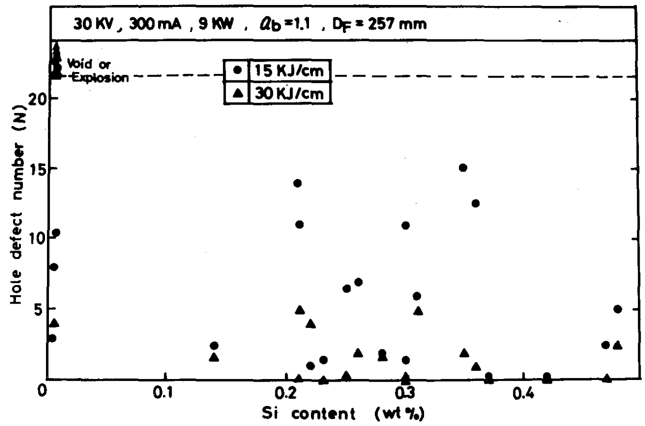

Fig. 15 Relation between Si content and hole defect number in weld metal for twenty different steels.

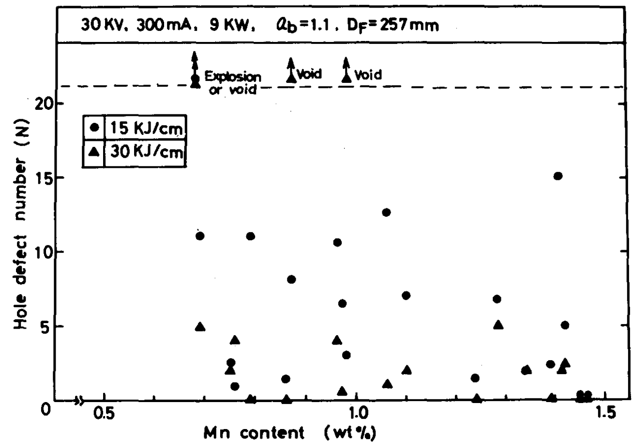

Fig. 16 Relation between Mn content and hole defect number in weld metal for twenty different steels.

and manganese contents in steels, respectively. It is likely that the hole defect number is not closely related to the variation of respective content within the limit in this investigation. However, referring to Fig. 15, the explosion- or void-type porosities have a tendency to occur in case of the materials, which hardly contains Si content, e.g. S2, S3 and R1 steels. Moreover it is found that those porosities also tend to occur in the materials with relatively low manganese content as shown in Fig. 16. From these results, it is obvious that the occurring of them is remarkably influenced by the quantity of de-oxidizer (for example Si and Mn etc.) which relates to the oxygen content in steel. Then Fig. 17 shows the relation between the oxygen content and the hole defect number in the weld metals whose nitrogen content is less than 54ppm. Because the A-porosity was hardly observed in the weld metal of Z1 steel, the nitrogen content of which is 54ppm, it is considered that the occurring of the porosity was not influenced by nitorgen content less than 54ppm. In general the hole defect number of A-porosity tends to be increased with an increase of oxygen content in steel. Moreover the void-type porosities began to occur in the weld metals more than 150ppm of oxygen content. Fig. 18 shows the relation between nitrogen content and hole defect number in weld metals. However the settlement was done for the weld metals less than 35ppm of oxygen content, as the A-porosity was not observed in the weld metal of Y2 steel, the oxygen content of which is 35ppm. The hole defect number was increased with an increase of nitrogen content in case of 15KJ/cm weld heat input, while it is hardly related with the variation of nitrogen content in case of 30KJ/cm weld heat input.

As above-mentioned, it was suggested that the occurring characteristics of weld porosities were influ-

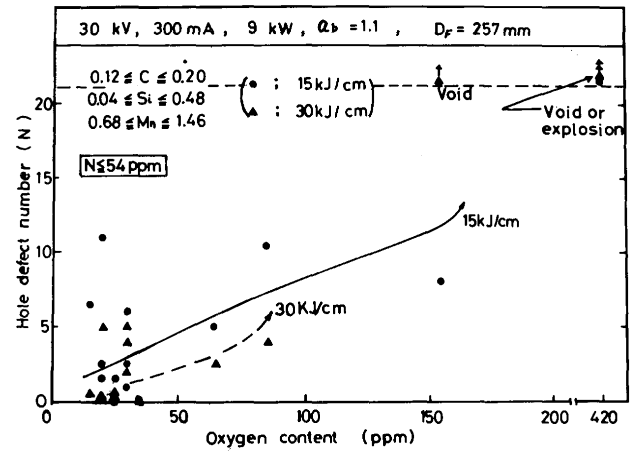

Fig. 17 Relation between oxygen content and hole defect number in weld metal for various materials.

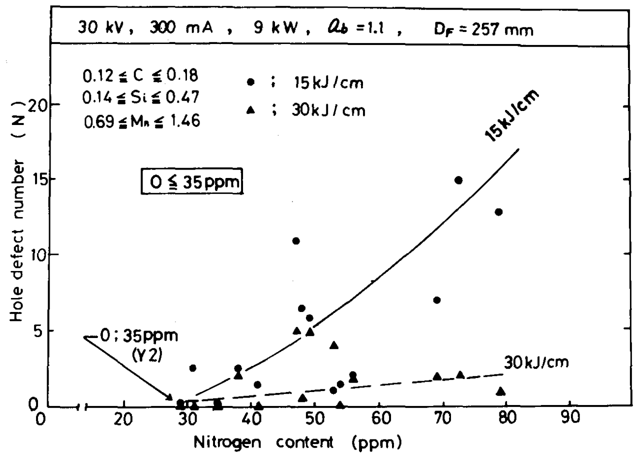

Fig. 18 Relation between nitrogen content and hole defect number in weld metal for various materials.

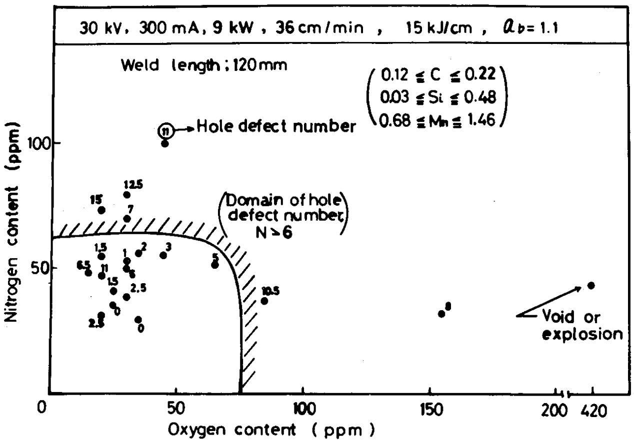

Fig. 19 Settlement for hole defect number by using nitrogen and oxygen contents in twenty different steels in case of 15KJ/cm weld heat input.

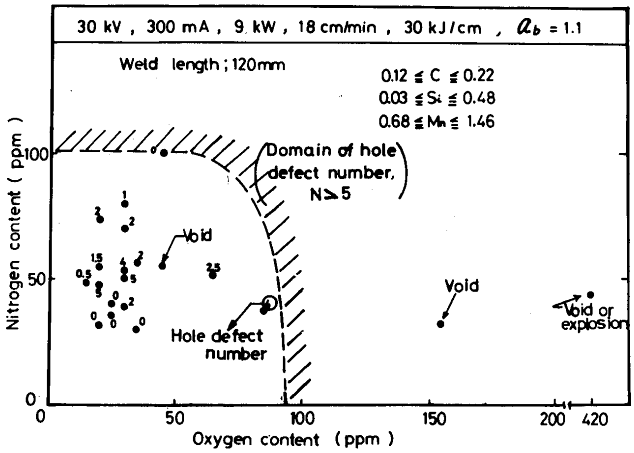

Fig. 20 Settlement for hole defect number by using nitrogen and oxygen contents in twenty different steels in case of 30KJ/cm weld heat input.

enced by both oxygen and nitrogen contents in various steels. Then the criteria of gas contents in the steel, for which a sound weld metal for porosities was obtained by electron-beam welding was settled by using oxygen and nitrogen contents. Fig. 19 and 20 show the results of settlement for the hole defect number by using nitrogen and oxygen contents in steel for 15 and 30KJ/cm weld heat inputs, respectively. The number on the points in each figure shows the hole defect number (N) of A-porosity. In Fig. 19 for 15KJ/cm weld heat input, the domain for N more than 6, which was shown by the oblique line was roughly made clear with one or two exceptions, and the synthetic grade for the welds of the materials in this domain was judged to the second or the worst class. On the other hand, in the materials of the domain for N less than 6, the sound weld metals were obtained, and the synthetic grade of them corresponds to the first calss. Then the allowable limit of the quantity for nitrogen and oxygen contents in steel is found to be less than about 60 and 70ppm in case of 15KJ/cm weld heat input, respectively. Nextly in Fig. 20 for 30KJ/cm weld heat input, the domain for N more than 5, which was also shown by the oblique line was roughly made clear, and the explosion-or void-type porosities occurred in this domain. Meanwhile in the domain inward the oblique line, the synthetic grade for the welds were the first calss with one exception of void-type porosity. Then in comparison with the result for 15KJ/cm weld heat input (Fig. 19), it is obvious that the allowable ranges for both nitrogen and oxygen in steel become to be wider with an increase of weld heat input in regard to the occuring of A-porosity.

5. Impact Properties

Fig. 21 through 25 show the impact test results against weld heat input for SS41, SM41, HT50, 60 and 80 weld metals, respectively. The testing temperature adopted was 0°C for SS41, SM41 and HT50, −5°C for HT60 and −1.5°C for HT80, which is specified for each steel by JIS or WES (Welding Engeneering Standard) Specification. In each figure the minimum value required for respective base metal prescribed by JIS or WES Specification is

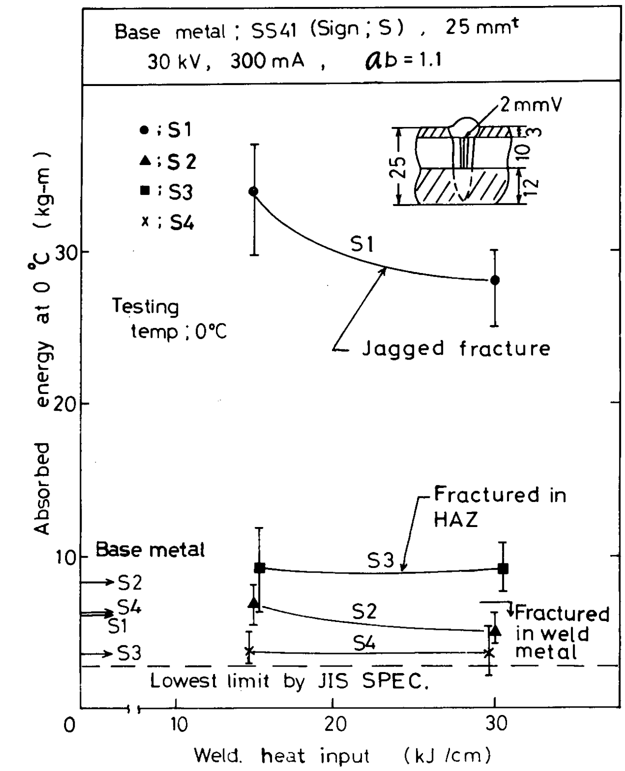

Fig. 21 Relation between weld heat input and absorbed energy at 0°C in various SS41 weld metals.

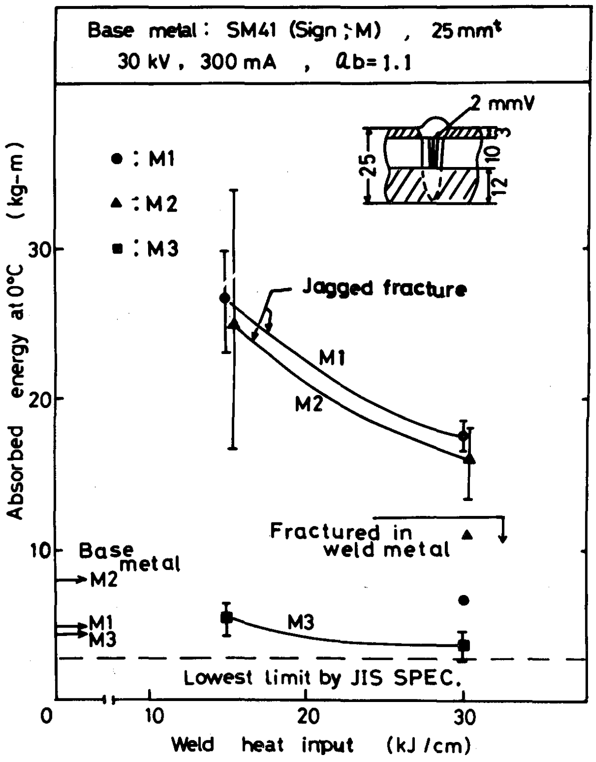

Fig.22 Relation between weld heat input and absorbed energy at 0°C in various SM41 weld metals.

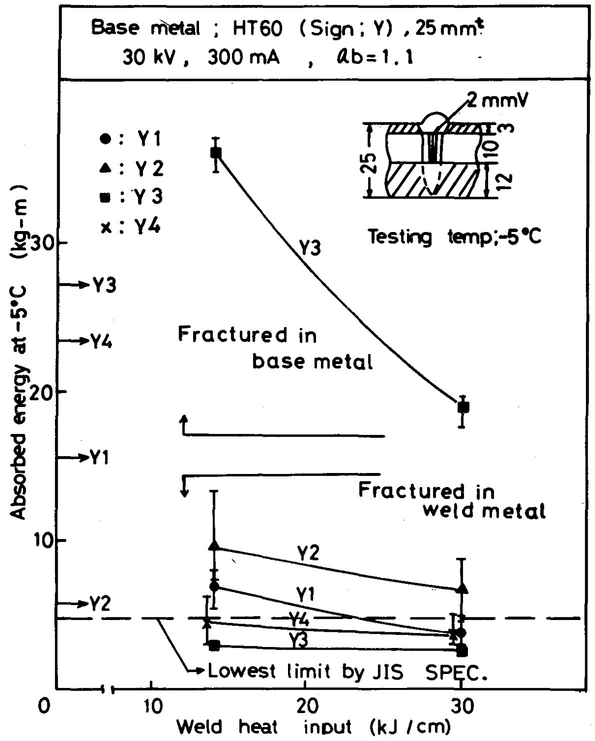

Fig. 24 Relation between weld heat input and absorbed energy at −5°C in various HT60 weld metals.

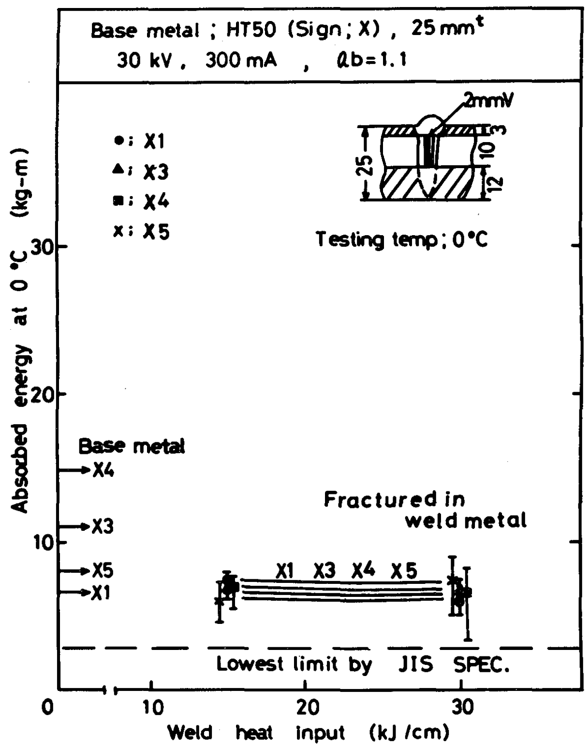

Fig. 23 Relation between weld heat input and absorbed energy at 0°C in various HT50 weld metals.

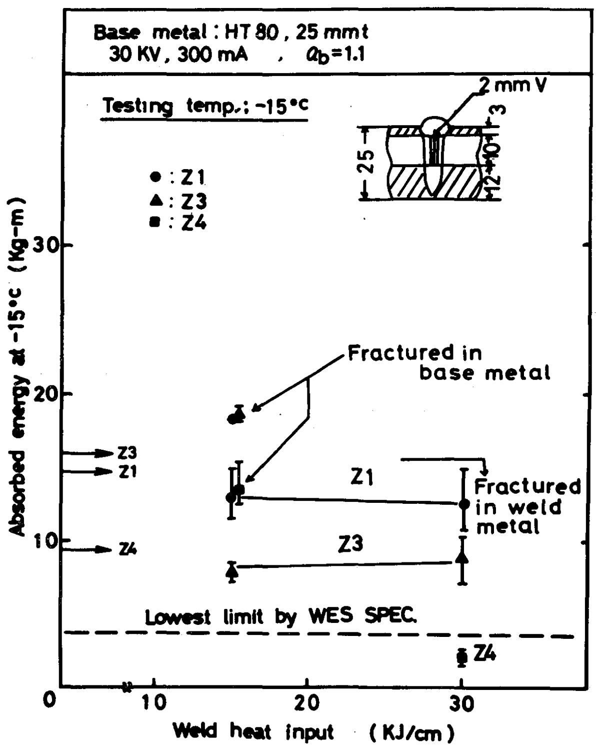

Fig. 25 Relation between weld heat input and absorbed energy at −15°C in various HT80 weld metals.

shown by the broken line as "Lowest limit".

As mentioned about the behavior on the transition temperature for fracture mode (Trm) in the previous report,[4] in the V-Charpy impact test for some of HT60 and HT80 weld metals, the fracture mode often deviates to the base metal side at higher than Trm, the absorbed energy of which shows remarkably high value as compared with that for fractured within weld metal. Furthermore in some of SS41 and SM41 welds, the absorbed energy shows relatively high value due to so-called "jagged fracture" though the fracture propagates within weld metal.

In general the impact strength of weld metal is irrespective of the variation of weld heat input within a limit of this investigation, and it showed lower than that for base metal in general. Moreover most of the weld metal are satisfied with the minimum value required in JIS or WES Specification, but some of HT60 and 80 weld metals are not satisfied with the Specification. This will be a theme for investigation in future.

6. Conclusions

By using twenty different constructional steels of 40 to 80Kg/mm^2 in strength, the relation between welding condition and weld porosities were firstly studied, and then the effect of chemical composition on the occurring characteristics of weld porosities were made clear. Furthermore, some of impact properties for those welds were investigated.

The results obtained are as follows.

(1) Bead shape and hardness examination

a) The bead shape tends to change from wedge-shaped type to wine cup-shaped type with an increase of a_b parameter, and the penetration depth becomes to be maximum at a_b :0.9.

b) There is no obvious variation in the average hardness of weld metal (Hw) for the variation of a_b parameter. In general the Hw tends to be increased with an increase of C_{eq}, however it is independent on the variation of C_{eq} for the materials of low C_{eq} (SS41 and SM41).

(2) Relation between welding condition and weld porosities.

a) The weld porosities observed were roughly divided into two classes, that is, Root-porosity in the bottom of weld penetration and A-porosity at the middle of weld penetration.

b) Root porosity tends to be decreased with an increase of a_b parameter, and meanwhile the amount of A-porosity occurred is the most in case of a_b: 1.1.

(3) Effect of chemical composition on weld porosities.

a) In general A-porosity has a tendency to be decreased with an increase of weld heat input, however huge porosities like void-type defect often occur in SS41 weld metal in case of large weld heat input of 30KJ/cm.

b) The amount of A-porosity occurred is not closely related to the variation of C, Si and Mn contents in steel within a limit of this investigation.

c) Huge porosities like void- or explosion-type defect was observed in the weld metal for the materials having extremely high oxygen content, and further A-porosity tends to be increased with an increase of nitrogen content in steel in case of low weld heat input of 15KJ/cm.

d) In case of low weld heat input of 15KJ/cm, the allowable limit in quantity for nitrogen and oxygen contents in steel was found to be less than about 60ppm and 70ppm, respectively, that is to say, the synthetic grade for the weld metal of those materials corresponds to the first class.

e) The allowable limit for nitrogen and oxygen contents in steel becomes to be raised with an increase of weld heat input concerning to the occurring of weld porosities.

(4) Impact properties

a) In general, the impact strength of weld metal is irrespective of the variation of weld heat input within a limit of this investigation.

b) The impact strength for most of weld metal are satisfied with the minimum value required in JIS or WES Specification, however in some of HT60 and 80 weld metals, they are not satisfied with the specification.

Acknowledgement

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