Welding Heat Input Limit of 780N/mm^2 Grade Steels and Low Yield Strength Steels Based on Simulated HAZ Tests†

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Abstract

In The Great Hanshin-Awaji Earthquake, the general yield brittle fractures were observed in beam-column connections of steel building frames. Among many influencing factors which affect the general yield brittle fracture, it can be considered that fracture toughness has substantial effects. Some studies are making clear the required toughness for the base metal and the weld metal, but general values are not proposed. Moreover, it seems that it is also important to pay attention to the toughness decrease in the weld heat affected zone (weld HAZ), because the toughness decrease occurs in the HAZs of mild steel.

In Ref. 1), the relationship between toughness of simulated HAZs of "the rolled steels for building structures (SN)" and the weld heat-input limit of the SN steel were investigated, in an attempt to provide the required toughness for HAZs. The relationships between the increase of the hardness value and toughness, and changes of microstructure after weld heat-input were also discussed.

In this paper, "780N/mm^2 grade steels" and "low yield strength steels" are examined. The main results are summarized as follows. (1) The reduction of ductility in CGHAZ of the HT780 by the welding heat-input are almost same as the general mild steels, SN400B and SN490B. (2) Even though the chemical compositions are not so different, the relationship between the Charpy absorbed energies and the equivalent heat-input are quite different to the low yield strength steels. It is inadvisable to fix a type of low yield steel to main structures by welding. (3) The results of Charpy impact test of the low yield steels are clearly divided into very high and very low because of their large grain size. So Charpy impact test is not appropriate for investigating the ductility of the low yield steels.

KEY WORDS: (Steel Structures) (Welded Joints) (Brittle Fracture) (Welding Heat-input) (Heat Affected Zone) (Simulated HAZ Test)(Fracture Toughness)(Charpy Absorbed Energy) (780N/mm^2 grade steel) (Low Yield Strength Steel)

1. Introduction

In The Great Hanshin-Awaji Earthquake, "general yield brittle fractures" were observed in beam-column connections of steel building frames. Many studies have been made of the influencing factors and about the energy absorption capacity of the general yield brittle fracture[2), 3)].

Among many influencing factors, it can be considered that fracture toughness has substantial effects, especially for fractures in beam-flanges. Some required toughness values are suggested to avoid the general yield brittle fracture, but more studies and discussion are needed to propose general values[4) - 6)].

Moreover, the fracture toughness of steels for building structures may be altered after experiencing thermal cycles imposed by welding processes. So it seems that it is also important to pay attention to the toughness decrease of the heat affected zone (weld HAZ), not merely the toughness of the base metal and the weld meal. In the present standard, lower limit values of the Charpy absorbed energy of base metals and weld metals are provided as the required toughnesses (these are to avoid the low stress brittle fracture). But the required

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toughness for HAZs is not provided.

In Ref. 1), the relationship between the toughness of HAZs of "rolled steels for building structures (SN400B and SN490B)" and the welding heat-input were investigated. The relationship between the increase of the hardness value and toughness, and changes of microstructure after welding heat-input were also discussed. The main results are summarized as follows. (1) The SN400B can keep its toughness at higher heat-inputs compare to the SN490B. (2) The steel grade, which becomes harder than other steel grades at the same heat-input, has smaller absorbed energy and smaller limit of heat-input. (3) In the case of the SN400B, which has more than 200J Charpy absorbed energy for no heat-input, the heat-input limit for the required toughness of 27J is over 87kJ/cm, that of 47J is at least 60kJ/cm and that of 85J is at least 37kJ/cm. (4) In the case of the SN490B, the heat-input limit to the required toughness of 27J is about 37kJ/cm, that of 47J is at least 16kJ/cm and that of 85J is very small heat-input, less than 10kJ/cm.

In this paper, "780N/mm^2 grade steels" and "low yield strength steels" are examined to investigate the relationship between the toughness of HAZs and the welding heat-input. Weld heat-input limits are proposed for some required toughness values. Usually multi-pass welding is used to connect the beam-flange to the diaphragm or the column flange. In this paper, single pass welding is examined as a first step.

2. Experimental details

2.1 Steel types

The 780N/mm^2 grade steels, named HT780, and the low yield strength steels, named LY steels, were used in this experiment. The tensile test results and the chemical compositions, which are written in the inspection certificate of each series, are shown in **Table 1** and the stress-strain relationship of the HT780 and the LY steels, are shown in **Fig. 1**. The stress-strain relationships of the rolled steel for building structures (SN400B and SN490B) are also shown in Fig. 1 to compare with the HT780 and the LY steels.

The HT780 has over 780N/mm^2 of tensile strength, but has a large yield ratio and small elongation capacity compared to the SN. In some parts of penstocks, skyscrapers and long bridges, for example the Akashi Kaikyo bridge that is the longest suspension bridge in the world, the HT780 was used in JAPAN. Two series of the HT780, named "HT780-1"and "HT780-2", were used in this study.

These two HT780s were made by different companies. As shown in Talbe 1, these contain much manganese (Mn) and other additional elements and, moreover, a thermal refining process is given to HT780 to raise the tensile strength.

The LY steels are developed to use as hysteresis dampers that absorbed the vibration energy of earthquakes[7]. So the LY steels require low yield strengths to yield before the main members and large elongation capacities to absorb large energies by hysteresis. Three grades of the LY steels, named "LY235", "LY180" and "LY90" were examined. They have different yield stress, 235MPa, 180MPa and 90MPa, but they all have very large elongation capacity, over 50%.

Many researches have examined how to use the LY steels as hysteresis dampers. In most of them, the LY steels are planned to be fixed to main members by welding. So it is very important to investigate the relationship between the toughness of HAZs and the welding heat-input.

The same company made the three LY steels. As shown in Table 1, carbon (C) and manganese (Mn) are reduced for low yield strength. Especially, the LY180 and LY90 contain less than 0.01% of carbon.

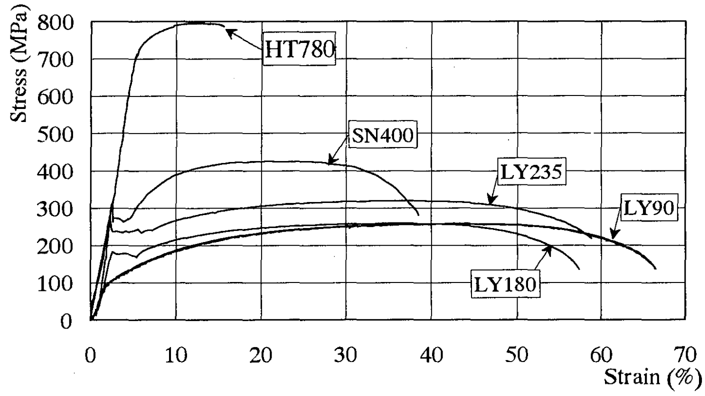


Fig.1 A example of stress– strain relationship in each steels

Table 1 Tensile test results and chemical composition of 780N/mm^2 grade steels and low yield strength steels

	Tensile test results				Chemical composition (%)												
	σ_y (MPa)	σ_u (MPa)	δ (%)	YR (%)	C	Si	Mn	P	S	Cu	Ni	Cr	Mo	V	B	PCM	Ceq
					$\times10^{-2}$			$\times10^{-3}$		$\times10^{-2}$				$\times10^{-3}$		$\times10^{-2}$	
HT780-1	706	814	21	87	11	26	99	9	3	22	3	62	33	40	1	24	49
HT780-2	789	842	19	94	19	23	145	9	1	-	-	-	-	-	1	28	44
LY235	235	321	50	73	6	1	26	18	11	-	-	-	-	-	-	7	10
LY180	180	266	53	68	0	1	8	6	3	-	50	-	-	-	-	1	3
LY90	91	265	56	34	0	1	16	13	4	-	-	-	-	-	Ti 40	1	3

2.2 Details of simulated HAZ tests

Not all regions of weld HAZ experience an equivalent decrease in toughness because of the distance from the molten weld pool. It has been shown that a remarkable toughness loss occurs in the coarse-grained heat affected zone (CGHAZ). The CGHAZ is a region immediately adjacent to the fusion zone where peak temperatures approach the melting point. To measure the toughness of CGHAZ is almost impossible by impact tests using actually welded specimens. Because the region of CGHAZ is so narrow it is difficult to adjust the tip of notch of the specimen and mechanical properties of the weld metal and HAZs around CGHAZ affect the toughness of CGHAZ. In this study, therefore, simulated weld CGHAZ specimens were used.

Samples, 55 × 12 × 9 mm, for the weld HAZ simulation were cut from as-received steel plates of 9mm thickness. A thermal/mechanical simulator, "Gleeble 1500", was employed to simulate the weld CGHAZ. The area between 5mm from the center of samples to the ±X-direction was heated by the thermal/mechanical simulator as shown later (Fig. 6).

Thermal cycles for the simulation of CGHAZs are schematically shown in **Fig. 2**. In these thermal cycles, the peak temperature was 1,350°C, and the holding time was 6s. Cooling rate from 1,350°C to 800°C and from 500°C to room temperature were the same in each temperature cycle[8]. Cooling rates from 800°C to 500°C were varied to simulate the CGHAZs with various heat-inputs. The microstructure of weld HAZs of low alloy steels has been said to be determined by the cooling rate from 800°C to 500°C. It has been also said that the cooling rate from 800°C to 500°C can estimate the welding heat-inputs[9].

The Charpy impact test was adopted to measure the toughness in this research. Sub-size, 55×10×7.5 mm, standard Charpy V-notch specimens were prepared from samples subjected the weld HAZ thermal cycle.

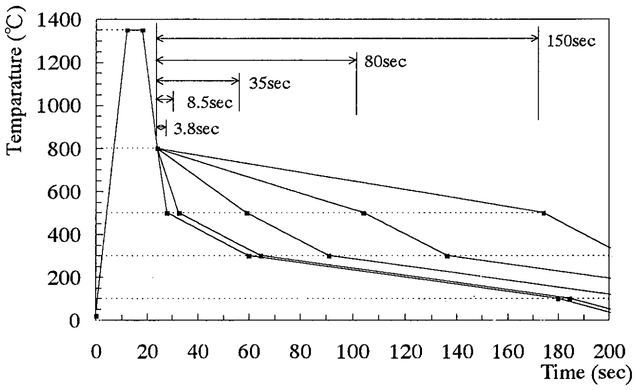


Fig. 2 Thermal cycle used to simulate weld CGHAZs

Table 2 Results Charpy impact test

Upper value: Charpy absorbed energy (J); lower value: Crystallinity (%)

	No heat treatment (0kJ/cm)					800-500 3.8sec (10kJ/cm)					800-500 8.5sec (16kJ/cm)				
	No.1	No.2	No.3	No.4	Ave.	No.1	No.2	No.3	No.4	Ave.	No.1	No.2	No.3	No.4	Ave.
HT780-1	263	242	249	238	248	90	88	217	137	133	79	200	217	104	134
	0	0	0	0	-	40	50	60	50	-	40	0	0	25	-
HT780-2	206	211	181	204	200	61	62	55	52	57	58	56	59	69	60
	0	0	0	5	-	60	60	65	60	-	60	65	60	70	-
LY235	266	292	297	291	286	3	342	352	357	264	73	336	17	340	191
	0	0	0	0	-	40	5	5	5	-	50	0	90	0	-
LY180	260	269	273	83	222	281	38	285	290	224	47	261	285	62	164
	0	0	0	60	-	10	90	5	5	-	80	0	0	80	-
LY90	32	213	213	256	179	10	10	7	7	8	12	10	9	9	10
	80	5	5	0	-	95	95	95	95	-	95	95	95	95	-

	800-500 35sec (37kJ/cm)					800-500 80sec (60kJ/cm)					800-500 150sec (87kJ/cm)				
	No.1	No.2	No.3	No.4	Ave.	No.1	No.2	No.3	No.4	Ave.	No.1	No.2	No.3	No.4	Ave.
HT780-1	193	222	68	119	164	24	33	20	45	31	20	19	12	9	15
	30	20	55	45	-	100	100	100	100	-	100	100	100	100	-
HT780-2	10	12	14	14	13	19	17	20	18	19	-	-	-	-	-
	100	100	100	100	-	100	100	100	100	-	-	-	-	-	-
LY235	22	16	54	27	30	14	16	12	17	15	15	12	14	11	13
	95	95	95	95	-	100	100	95	95	-	95	100	100	100	-
LY180	68	275	281	341	241	89	273	67	266	174	49	271	286	283	222
	70	0	0	0	-	60	0	70	0	-	80	0	0	0	-
LY90	10	11	10	8	10	9	11	10	11	10	10	11	10	12	11
	95	95	95	95	-	95	95	95	95	-	95	95	95	95	-

2.3 Relationship between cooling ratio and heat-input

According to Ref. 9), the following relationships between the cooling ratio from 800°C to 500°C and the welding heat-input by CO_2 shielded gas welding were adapted.

$$S = \frac{J^{1.7}}{2.9\cdot(600-T_0)^2\left\{1+\frac{2}{\pi}\tan^{-1}\left(\frac{t-13}{3.5}\right)\right\}} \quad \cdots(1)$$

S : Cooling ratio from 800°C to 500°C (sec)
J : Welding heat-input (J/cm)
t : Thickness of welded member (mm)
T_0 : Temperature of steel before welding (°C)

Using these equations, the cooling rate can be calculated by the welding heat-input in CO_2 shielded gas welding. Assuming that the thickness of the welded beam-flange is 20mm and temperature of the beam-flange before welding is 20°C as a typical value, cooling rates from 800°C to 500°C are calculated as follows.

CO_2 heat-input: 10kJ/cm → cooling ratio: 3.8 sec
CO_2 heat-input: 16kJ/cm → cooling ratio: 8.5 sec
CO_2 heat-input: 37kJ/cm → cooling ratio: 35 sec
CO_2 heat-input: 60kJ/cm → cooling ratio: 80 sec
CO_2 heat-input: 87kJ/cm → cooling ratio: 150 sec

We call these CO_2 heat-input values (10kJ/cm, 16kJ/cm, 37kJ/cm, 60kJ/cm and 87kJ/cm) as "the equivalent heat-input" in this paper.

As shown later (Fig. 7 and Fig. 8), the Vickers hardness values of the area between about ±10mm from the center are almost stable and it suggests that the area represents a uniform CGHAZ.

3. Results and discussion

3.1 Relationship between toughness of HAZs and heat-input

Table 2 shows the Charpy absorbed energy and the crystallinity of each series. The Charpy absorbed energy values are converted into full-size specimen values by multiplying the section area-ratio of the full-size and the sub-size specimen (4/3).

Fig. 3 and **Fig. 4** show the relationship between the Charpy absorbed energies and the equivalent heat-input. Three parallel lines were drawn in these figures without curve fitting in each figure. The meaning of the each line and its absorbed energy values are as follows.

a) Solid lines: This line shows 85J. This value is proposed in Ref. 8) to avoid the general yield brittle fracture. But this is proposed for a comparatively uniform part like the weld metal and the base metal. So it seems that the specimens without welding heat-input in each series should have higher Charpy absorbed energy values than this.
b) Dotted lines: This line shows 47J. This value is required for some weld metals and base metals in JIS (Japan Industrial Standard). This is the maximum value required for the weld metal and the base metals used for building structures, generally. But this value is proposed to avoid the low stress brittle fracture not to avoid the general yield brittle fracture.
c) Dot-dash lines: This line shows 27J. This value is also required for some weld metals and base metals and this value is also proposed to avoid the low stress brittle fracture.

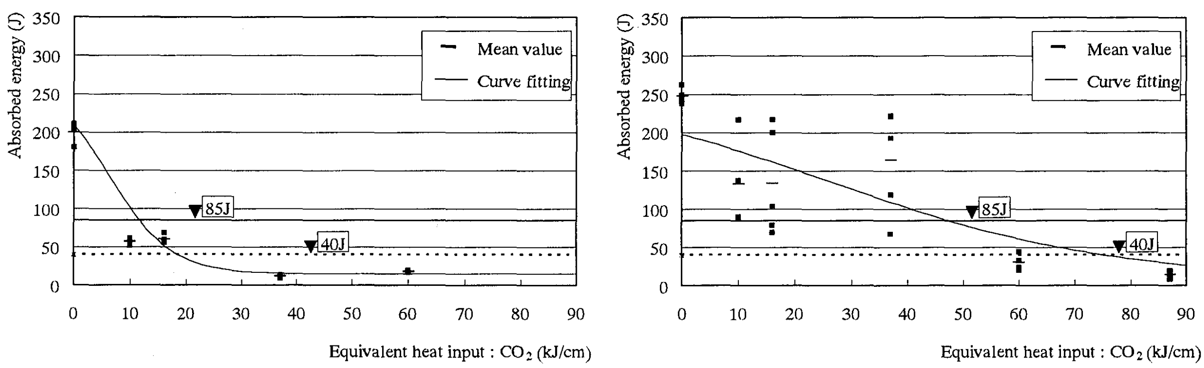
As mentioned in section 1, the toughness values to avoid the general yield brittle fracture are not yet clear. So these values are used in this paper as yardsticks. The Charpy impact test results in this experiment are compared with these three values.

The curve-fit are lined in these figures. This equation of curve-fit is usually used for the temperature transition curve[1), 10)].

3.1.1 *Toughness decrease of HT780s by welding heat-input*

With increasing cooling rate from 800°C to 500°C, that is with decreasing equivalent heat-input, the Charpy absorbed energy of the HT780 tends to decrease in all series. But decreasing rates are different in each series.

The HT780-1 and the HT780-2 have large absorbed energy (over 200J) much more than 85J for no welding heat-input (equivalent heat-input = 0 kJ/cm). In the case of the HT780-1, after equivalent heat is inputted,



(a) HT780-1 (b) HT780-2

Fig. 3 Relation between Charpy absorbed energy and equivalent weld heat input (780N/mm^2 grade steels) the means of absorbed energy gradually decrease to 85J between 37 kJ/cm and 60kJ/cm, and decrease to 47J for about 60kJ/cm. For large equivalent heat-inputs, about 87kJ/cm, it decreases to 27J. In the case of the HT780-2, decrease of the means of absorbed energy become more significant and energy decreases to under 85J for about 10kJ/cm and decreases to below 27J for about 37kJ/cm. From the above results, it could be said that the HT780s, which have more than 200J Charpy absorbed energy for no heat-input, can meet 47kJ at least until 16kJ/cm. But one type of the HT780 cannot meet 85kJ at small heat inputs and cannot meet 27kJ at 37kJ/cm.

As mentioned above, it seems that the specimens without welding heat-input in each series should have higher Charpy absorbed energy values than 85J. All HT780s satisfy this. If we use 47J and 27J as criteria of ductility, it seems that the heat-input remit of HT780 is between 16kJ/cm and 37kJ/cm.

3.1.2 Toughness decrease of LY steels by welding heat-input

As shown in Table 1, the chemical compositions of the LY steels are not so different, especially the chemical compositions of LY180 and LY90 are very similar. But the relationship between the Charpy absorbed energies and the equivalent heat-input are quite different.

The LY235 has very large absorbed energy (near to 300J) much more than 85J for no welding heat-input. After equivalent heat is inputted, the Charpy absorbed energy of the LY235s also tends to decrease gradually with decreasing equivalent welding heat-input the same as in the case of mild steels and HT780s. The means of absorbed energy decrease to 85J and 47J between 16kJ/cm and 37kJ/cm, and decrease to 27J for about 37kJ/cm. If we use 47J and 27J as criteria of ductility, it seems that the heat-input remit of LY235 is between 16kJ/cm and 37kJ/cm. But the test results for heat-inputs 10kJ/cm and 16kJ/cm are clearly divided into very high and very low.

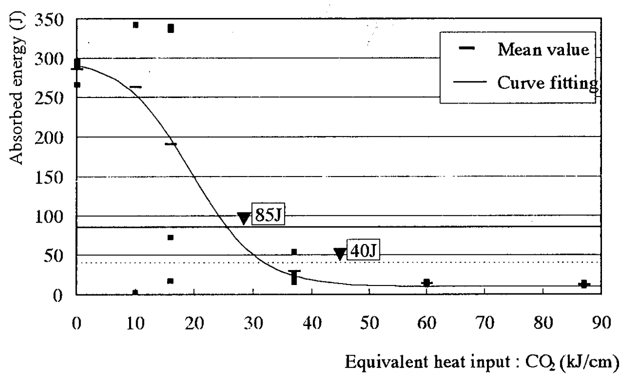
This tendency is observed in the results of the LY180s at all heat-inputs, even for no heat-input. The reason for the tendency is discussed latter. The means of absorbed energy are very high (about 200J) at all heat-input, and are divided into under 85J and over 250J . But all specimens, except one, have more over 47J. It can be said that the Charpy absorbed energy of the LY180 is little affected by welding heat-input.

The YL90 also has large absorbed energy, much more than 85J, and also has the tendency observed in the other LY steels for no welding heat-input. But quite different from the LY180 after equivalent heat is inputted, all specimens show the very low Charpy absorbed energy (about 10J) even at a very small heat-input, 10kJ/cm. It can be said that the Charpy absorbed energy of the LY90 is very sensitive to welding heat-input and it is inadvisable to fix LY90 to main structures by welding.

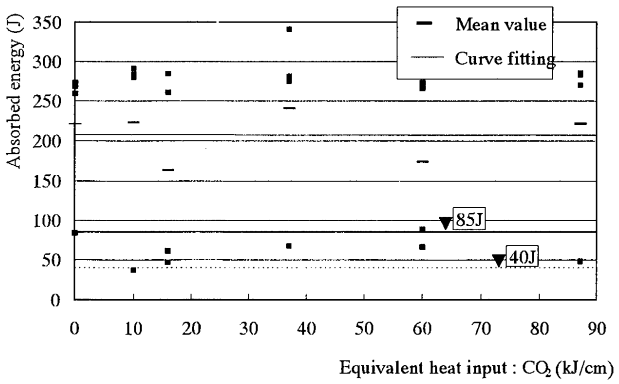
3.1.3 Comparison between HT780s and mild steels

Fig. 5 shows the means of Charpy absorbed energy of every HT780 and all HT780s for every equivalent welding heat-input. The means of all SN400Bs and SN490Bs are also shown in Fig.5.[1)] Differing from the Fig.4 in Ref. 1), the SN400-3, that has very small Charpy absorbed energy compared to the others even for no heat-input, is included with the means of SN400s.

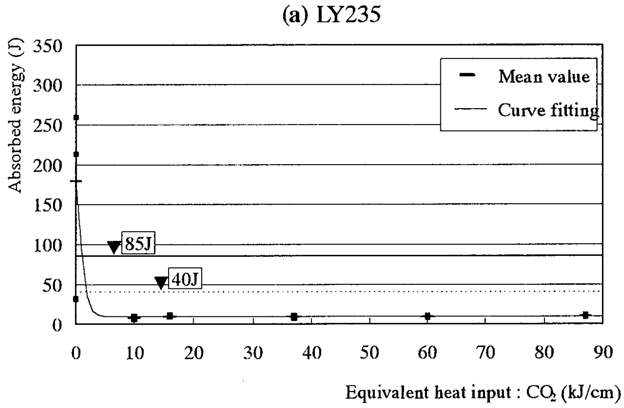
For no heat-input, the means of all HT780s are larger than the means of all SN400s and all SN490s. After the heat-input, the means of HT780-1 are almost same as the means of SN400Bs, and the means of HT780-2 are almost same as the means of SN490Bs. The means of all HT780s are in between the means of all SN400Ns and all SN490s for every equivalent welding heat-input.



(a) LY235



(b) LY180



(c) LY90

Fig. 4 Relationship between Charpy absorbed energy and equivalent weld heat input (low yield strength steels)

Therefore, it could be said that the reduction of ductility in the CGHAZ of the high-grade steel, HT780, by the welding heat-input are almost same as mild steels, like SN400B and SN490B, which are generally used in JAPAN.

3.2 Changes of hardness value

The micro Vickers hardness machine (weight = 9.8N) was used to compare changes of hardness after welding heat-input. The no heat-input specimens were tested every 2mm and the heat-input specimens were tested every 0.5mm or 1mm from the center to +20mm and -20mm of X-direction. Measured points of the heat-input specimen are shown in **Fig. 6**. **Fig. 7** and **Fig. 8** show the Vickers hardness test results of HT780s and LY steels.

In the case of the HT780s, the Vickers hardness values for no heat-input are very high (about 270HV), but softness is observed outside the heated zone after heat-input. It seems that it is due to the thermal refining processing. But the hardness near the V-notch, which seems to affect the Charpy impact test, are almost stable. The hardness near the V-notch tends to become large from 20 ～ 70HV after a 37J/cm heat-input.

In the case of the LY steels, the Vickers hardness values for no heat-input are very low (about 100HV). The hardness near the V-notch of LY234 and LY90 tends to become large after a 37J/cm heat-input. The hardness of the LY90 become 150HV after 37J/cm heat-input, and it is 1.5 times the hardness for no heat-input. From point of view of the increase of hardness, it can be said that the LY90 is very sensitive to welding heat-input. But the hardness of the LY180 does not become large at all after a 37J/cm heat-input. The hardness test results, shown Fig.8 (a), have smaller absorbed energy (67J) than others (more over 250J). So it seems that the scattering of absorbed energy is not caused by the scattering of hardness in LY180.

Fig. 9 shows the relationship between increasing ratio of Vickers hardness and decreasing ratio of Charpy absorbed energy. The increasing ratios of hardness are calculated by the means from -4mm to +4mm in the X-direction. The relationship between the absolute value of the hardness and the absolute value of the absorbed energy, and between the increment of the absorbed energy and the decrement of the hardness are hardly shows a correlation. The relationship between increasing ratio of hardness and decreasing ratio of absorbed energy shows a correlation, but it is not so strong.

3.3 Microstructures after welding heat-input

Fig. 10 and **Fig. 11** show photos of the microstructures of the HT780-2 and the LY180 for no heat-input and for a welding heat-input 37kJ/cm. These are typical of each steel grade.

The microstructures of the HT780s consist mainly of pearlite and ferrite. After the welding heat-input, both grains became refined. It seems that this is the cause for increasing of the Vickers hardness values.

On the other hand, the microstructures of the LY

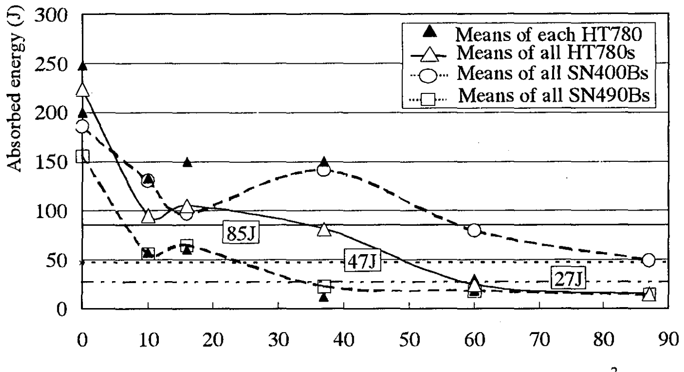


Fig. 5 Comparison between 780N/mm^2 grade steels and mild steels

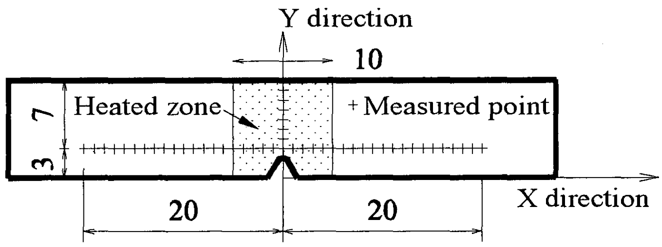
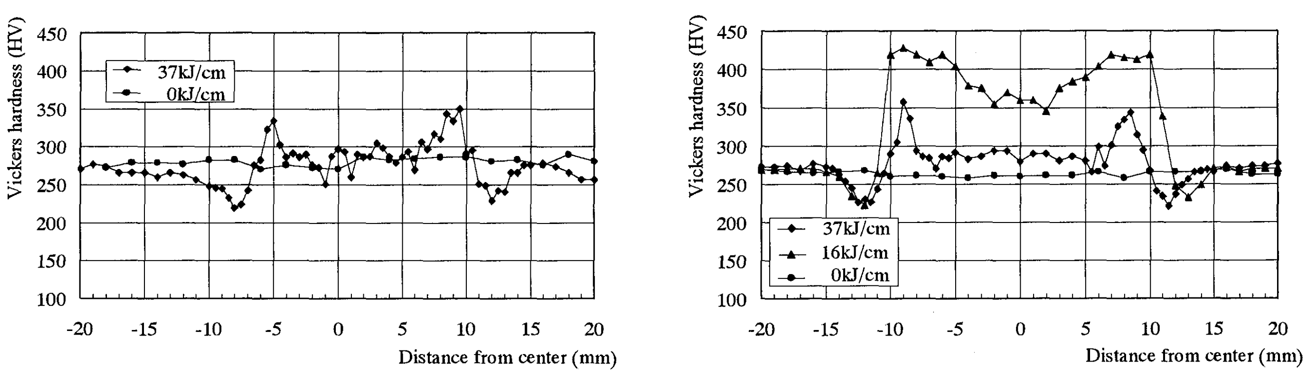


Fig. 6 Measured points of Vickers hardness test



(a) HT780-1 (b) HT780-2

Fig. 7 Results of Vickers hardness test (780N/mm^2 grade steels)

steels mainly consist of ferrite. Especially in the LY180s and LY90, martensite was not observed at all and grain sizes of ferrite were large. It could be said that the dispersion of the Charpy absorbed energy in the LY steels was caused by this largeness of grains. The absorbed energy will change in the direction where the grains line up from the top of the notch. After the welding heat-input, a change of the microstructures of the LY180s is not observed. But grain sizes of ferrite in LY90s become larger with welding heat-input. It seems that the residual elements, for example phosphorus and sulfur, will segregate in the grain boundary. It could be said that this is the cause of the decrease of absorbed energy of the LY90s after welding heat-input.

4. Conclusions

In this paper, the relationship between the toughness of simulated CGHAZs of the 780N/mm^2 grade steels (HT780) and the low yield strength steels (LY steels) and the welding heat-input limit are investigated. The investigation results are summarized as follows.

(1) The reduction of ductility in CGHAZ of the HT780 by the welding heat-input are almost same as general mild steels, SN400B and SN490B.
(2) If we use 47J and 27J as criteria of ductility, it seems that the heat-input remit of HT780 is between 16kJ/cm and 37kJ/cm.
(3) Even though the chemical compositions are not so different, the relationship between the Charpy absorbed energies and the equivalent heat-input are quite different to the LY steels. And it is inadvisable to fix a type of LY steels to main structures by welding.
(4) Only the relationship between increasing ratio of hardness and decreasing ratio of absorbed energy shows a correlation, but it is not so strong.
(5) The results of Charpy impact test of the LY steels are clearly divided into very high and very low because of large grain sizes. Charpy impact tests are not competent to investigate the ductility of the LY steels.

To determine the required toughness value, which includes the effect of the toughness mismatch, of CGHAZs to avoid the general yield brittle fracture will require more experimental results. But it seems better to design to avoid stress concentration points or defects in CGHAZs, because brittle points exist in CGHAZs after high heat-input welding.

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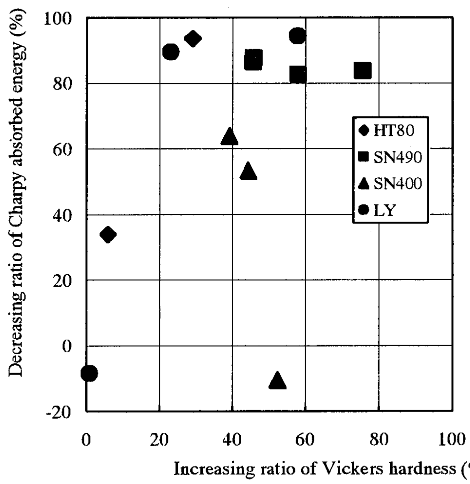


Fig. 9 Relationship between increasing ratio of Vickers hardness and decreasing ratio of Charpy absorbed energy

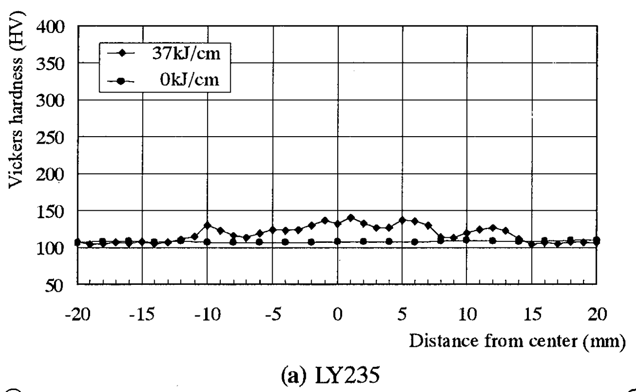
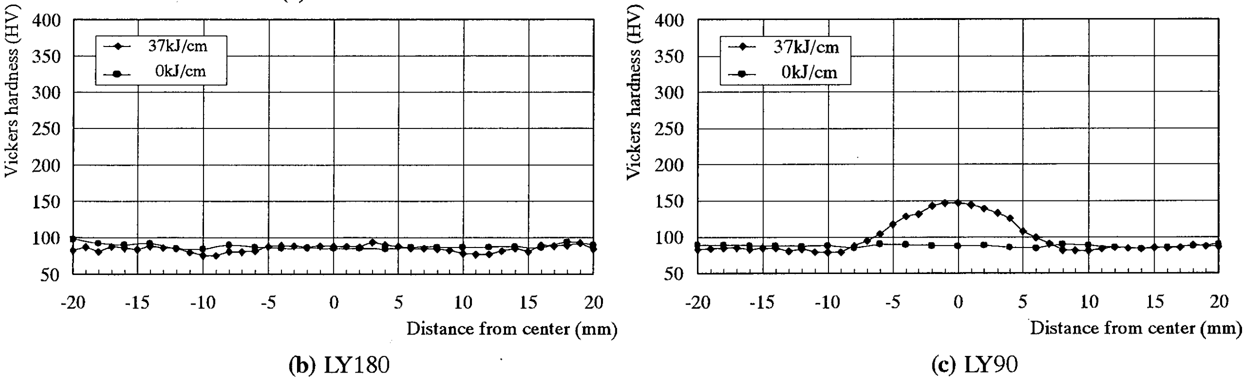
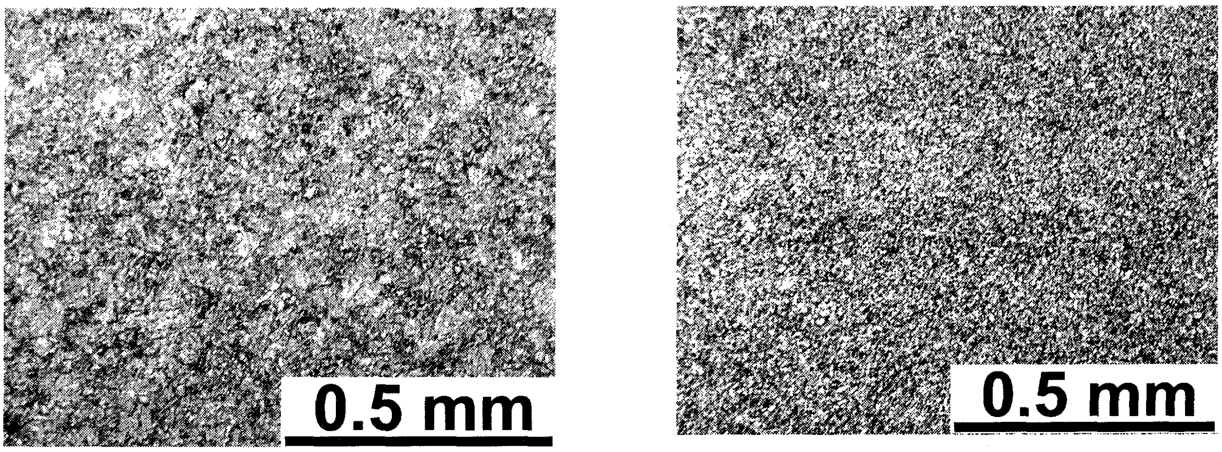
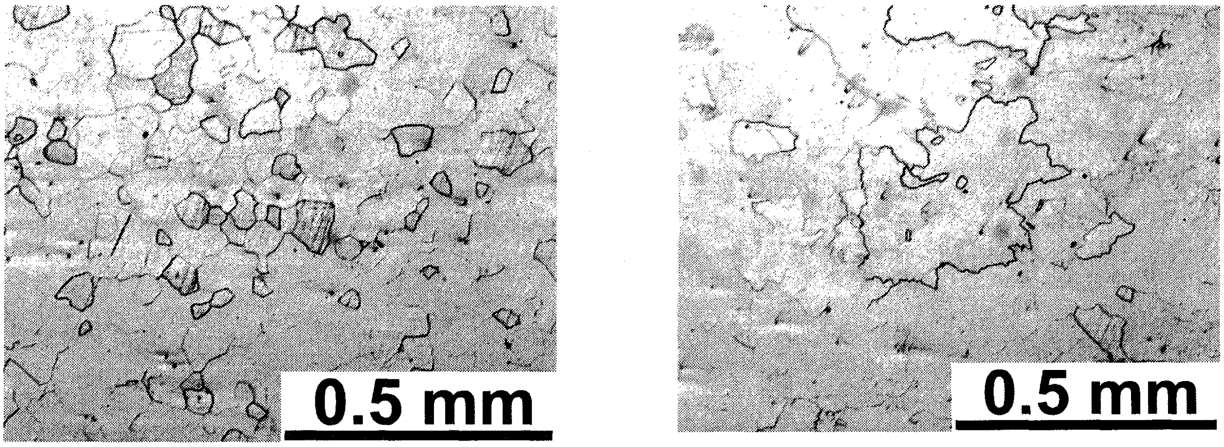



Fig. 8 Results of Vickers hardness test (low yield strength steels)



(a) No heat-input (b) Welding heat-input 37kJ/cm

Fig. 10 Microstructures of $780N/mm^2$ grade steels (HT780-2)



(a) No heat-input (b) Welding heat-input 37kJ/cm

Fig. 11 Microstructures of low yield strength steels (LY90)

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