Title	Welding Heat Input Limit of Rolled Steels for Building Structures Based on Simulated HAZ Tests(Mechanics, Strength & Structure Design)
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Citation	Transactions of JWRI. 2001, 30(1), p. 127-134
Version Type	VoR
URL	https://doi.org/10.18910/9726
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Welding Heat Input Limit of Rolled Steels for Building Structures 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 occurrs in the HAZs of mild steel.

In this paper, 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 are 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 are also discussed.

The main results are summarized as follows. 1) The SN400B can keep its toughness at higher heat-inputs compare to the SN490Bs. 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) The weld heat-input limit of the SN400B and the SN490B are proposed separately for some required toughness values.

KEY WORDS: (Steel Structures) (Welded Joints) (Brittle Fracture) (Welding Heat-input) (Heat Affected Zone) (Simulated HAZ Test)(Fracture Toughness)(Charpy Absorbed Energy) (Vickers Hardness Test)

1. Introduction

In The Great Hanshin-Awaji Earthquake, brittle fractures were observed in beam-column connections of steel building frames. These parts have the largest load, so that they become the most important part of the frame. It was ascertained by marks of local buckling, peeling of paint or mill scale and Luders's lines, that these fractured after plastic deformations. In this context, these are regarded as "general yield brittle fractures", because they fractured at stress concentration points or discontinuous points of shape after absorption of seismic energy.[1) - 5)] Many studies continued about the influencing factors and about the energy absorption capacity of the general yield brittle fracture.[6) - 9)]

Among many influencing factors, it can be considered that the fracture toughness has substantial effects, especially for fractures in beam-flanges. The beam-flanges were one of the most damaged parts. Welding connections of the beam-flanges to diaphragms or column-flanges were mainly damaged. Some studies are making clear the required toughness for base metal and weld metal to avoid the general yield brittle fracture. Some required toughness values are suggested, but more studies and discussion are needed to propose general values.[10) - 12)]

Moreover, the fracture toughness of steels for building structures may be altered after experiencing thermal imposed by welding processes. Many studies have showed that the toughness decrease occurred in the heat affected zone (weld HAZ) of most low alloy steels, include mild steels.[13)] So it seems that it is also important to pay attention to the toughness decrease of HAZs, not merely the toughness of the base metal and the weld meal. In the present standard, lower limit

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Transactions of JWRI is published by Joining and Welding Research Institute of Osaka University, Ibaraki, Osaka 567-0047, Japan.

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 toughness for HAZs is not provided at all.

In this study, therefore, the relationship between the toughness of HAZs of rolled steels for building structures and the welding heat-input are investigated. The relationship between the increase of the hardness value and toughness, and changes of microstructure after welding heat-input are also discussed. Usually multi-pass welding is used to connect the beam-flange to the diaphragm or the column flange. But in this paper, single pass welding is examined as a first step.

2. Experimental details

2.1 Steel types and grades of specimens

The rolled steels for building structures, named "SN", were used in this experiment. As shown in the name, the SN series was established for building frames in 1994. To keep the plastic deformation capacity of the frame, upper and lower limits of the yield stress and the tensile strength, an upper limit of the yield ratio and a lower limit of the elongation are provided in JIS (Japan industrial standard).

The SN has three types, named "SN-A", "SN-B" and "SN-C". The SN-A is not permitted to be welded and a lower limit of absorbed energy in Charpy impact test is not provided. The SN-B is permitted to be welded and a lower limit of Charpy absorbed energy, 27J at 0°C, is provided. Only the SN-C is permitted to be used in weld cruciform connection members, which are forced to the thickness direction. A lower limit of Charpy absorbed energy, 27J at 0°C, is also provided. Some chemical compositions are limited in each type.

The SN has two grades, 400 and 490. The number indicates a lower limit of tensile strength and the yield stress values for the structural design are decided as 235MPa and 325MPa. The chemical compositions is also limited in each grade.

In the experiment, the SN-B type was used because the SN-B is usually used as the beam-flange welded to column-flange or diaphragm. As already mentioned above, the beam-flange is one of the most damaged parts in The Great Hanshin-Awaji Earthquake. Both of the 400 grade and the 490 grade are used in the experiments because both of them are used as beam-flanges. Three series of the SN400B (named SN400-1～SN400-3) and four series of the SN490B (named SN490-1～SN490-4) were used. All steels of each series were made by different companies.

The tensile test results and the chemical compositions, which are written in the inspection certificate of each series, are shown in **Table 1.**

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 remarkable toughness loss occurs in the coarse-grained heat affected zone (CGHAZ). 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 fthe center of samples to the ±X-direction was heated by the thermal/mechanical simulator as shown later (Fig. 4).

Thermal cycles of the simulation of CGHAZs are schematically shown in **Fig. 1**. In these thermal cycles, the peak temperature was 1350 °C, and the holding time was 6s. Cooling rate from 1350°C to 800°C and from 500 °C to room temperature were same in each

Table 1 Tensile test results and chemical composition of SN400Bs and SN490Bs

	Tensile test results				Chemical composition (mass %)											
	σ_y	σ_u	δ	YR	C	Si	Mn	P	S	Cu	Ni	Cr	V	Mo	B	Ceq
	(MPa)	(MPa)	(%)	(%)	$\times 10^{-2}$			$\times 10^{-3}$		$\times 10^{-2}$			$\times 10^{-3}$			$\times 10^{-2}$
SN400-1	337	448	29	75	9	23	64	23	10	18	8	15	0	30	0.5	25
SN400-2	312	430	34	73	7	24	134	14	3	-	1	4	0	-	-	31
SN400-3	374	452	32	83	11	22	98	12	4	-	1	2	1	0	-	28
SN490-1	388	527	26	74	15	28	149	13	3	-	2	3	2	1	-	42
SN490-2	435	554	24	79	16	24	139	17	3	-	2	4	2	2		41
SN490-3	338	529	25	64	16	34	145	18	3	-	2	4	0	0	-	42
SN490-4	400	556	23	72	16	36	136	11	5	-	2	4	4	0	-	41

temperature cycle.[13] Cooling rates from 800°C to 500°C were varied to simulate the CGHAZs with various heat-inputs. Because 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.[14]

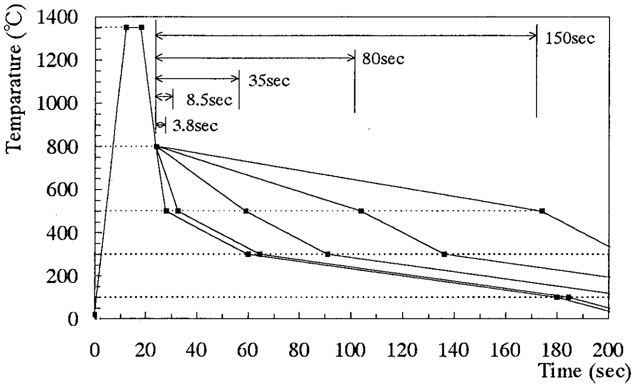


Fig.1 Thermal cycle used to simulate weld CGHAZs

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.

2.3 Relationship between cooling ratio and heat-input

According to the reference 14) and 15), the following relationships between the cooling ratio from 800°C to 500°C and the welding heat-input were adapted.

Table 2 Results Charpy impact test

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

	No heat treatment					800-500 3.8sec					800-500 8.5sec				
	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.
SN400	211	236	247	256	234	24	64	210	28	116	23	44	160	128	89
-1	0	0	0	0	-	95	95	25	90	-	95	95	60	80	-
SN400	299	264	291	196	263	206	340	95	280	230	132	234	192	161	180
-2	0	0	0	0	-	50	10	95	35	-	60	95	60	70	-
SN400	56	56	55	59	56	42	35	40	46	44	3	35	31	22	23
-3	0	0	0	0	-	75	70	50	50	-	100	100	100	95	-
SN490	203	168	255	193	205	68	77	60	34	81	40	99	90	65	73
-1	0	0	0	0	-	80	70	80	90	-	85	85	75	80	-
SN490	114	126	132	120	123	68	54	61	59	60	79	78	90	72	80
-2	0	10	30	15	-	50	60	60	60	-	40	30	20	60	-
SN490	140	136	132	151	139	54	69	53	53	57	65	77	78	69	73
-3	0	20	5	20	-	60	70	75	65	-	60	60	50	60	-
SN490	187	175	158	104	156	29	27	22	26	26	36	39	31	30	34
-4	15	30	45	70	-	90	95	95	90	-	90	95	95	90	-

	800-500 35sec					800-500 80sec					800-500 150sec				
	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.
SN400	19	234	123	69	111	68	18	27	43	36	15	27	20	37	25
-1	95	0	80	95	-	95	100	95	95	-	100	100	100	95	-
SN400	282	248	307	312	291	305	311	18	116	187	143	40	31	79	73
-2	40	55	0	0	-	20	20	95	90	-	80	100	100	95	-
SN400	30	7	31	14	20	18	3	26	15	16	34	31	35	34	33
-3	100	100	100	100	-	100	100	100	100	-	95	100	95	95	-
SN490	22	20	34	25	25	18	19	25	33	24	10	21	12	14	14
-1	95	100	100	95	-	95	100	100	95	-	100	100	100	100	-
SN490	23	14	26	18	20	10	17	17	14	16	-	-	-	-	-
-2	100	100	100	95	-	100	100	100	100	-	-	-	-	-	-
SN490	26	22	19	31	24	12	10	14	9	11	-	-	-	-	-
-3	100	95	95	100	-	95	100	100	100	-	-	-	-	-	-
SN490	26	22	14	22	21	17	35	18	22	23	-	-	-	-	-
-4	100	95	95	100	-	100	100	100	100	-	-	-	-	-	-

a) Submerged arc welding

$$S=\frac{9.5\cdot J^{(2.5-0.05t)}}{10^{5-0.22t}(600-T_0)^2\left\{1+\frac{2}{\pi}\tan^{-1}\left(\frac{t-12}{3}\right)\right\}}\qquad\cdots(1)$$

b) CO_2 shielded gas welding

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

c) Coated electrode arc welding

$$S=\frac{1.35\cdot J^{1.5}}{(600-T_0)^2\left\{1+\frac{2}{\pi}\tan^{-1}\left(\frac{t-14.6}{6}\right)\right\}}\qquad\cdots(3)$$

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 this study, we used equation (2), because almost of the beam-flanges are welded by CO_2 shielded gas welding. The welding heat-inputs were varied about 10, 15, 40, 60 and 80 kJ/cm. Assuming that the thickness of the welded beam-flange is 20mm and temperature of the beam-flange before welding as a typical value, cooling rates from 800°C to 500°C are calculated as follows.

CO_2 heat-input: 10kJ/cm
800°C→500°C cooling ratio: 3.8 sec
CO_2 heat-input: 16kJ/cm
800°C→500°C cooling ratio: 8.5 sec
CO_2 heat-input: 37kJ/cm
800°C→500°C cooling ratio: 35 sec
CO_2 heat-input: 60kJ/cm
800°C→500°C cooling ratio: 80 sec
CO_2 heat-input: 87kJ/cm
800°C→500°C 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.6), 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.

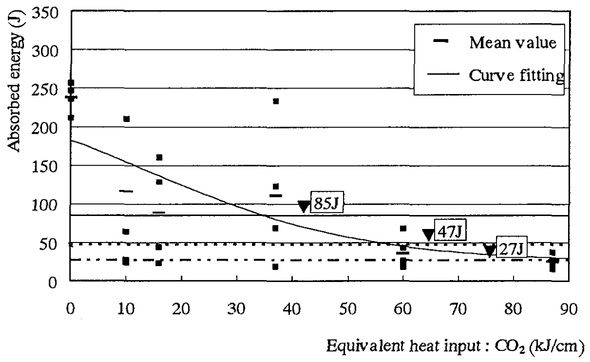
3. Results and discussion

3.1 Relationship between toughness of HAZs and heat-input

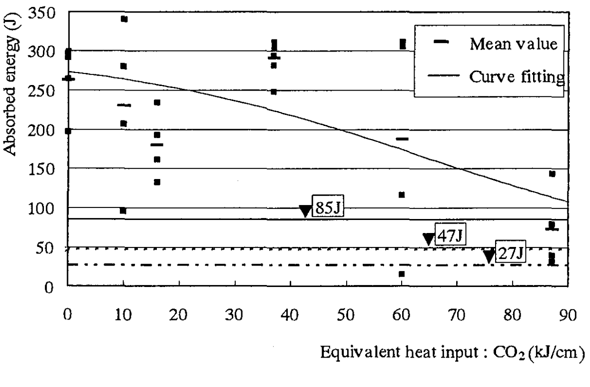
Table 2 shows the Charypy absorbed energy and the crystallinity of each series. The Charypy absorbed energy values are converted into full-size specimen values by multiplying the section area-ratio of the full-size and the sub-size specimen (4/3).

Fig. 2 and **Fig. 3** show the relationship between the Charpy absorbed energies and the equivalent heat-input. Three parallel lines were drawn in these figures without curve fitting line in each figure. The meaning of the each line and its absorbed energy values are as follows.

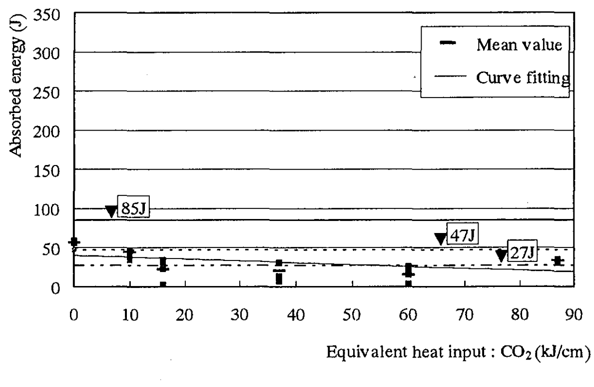
a) Solid lines: This line shows 85J. This value is proposed in reference 13) to avoid the general yield



(a) SN400-1



(b) SN400-2



(d) SN400-3

Fig. 2 Relation between Charpy absorbed energy and Equivalent weld heat input (SN400B) 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. This is the maximum value required for the weld metal and the base metals used for building structures, generally. But, as mentioned above, 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 include the SN-B, and this value is also proposed to avoid the low stress brittle fracture.

As mentioned in the 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 following equation is used to curve-fit. This equation is usually used for the temperature transition curve. In these figures, we replace equivalent heat-input for temperature,[16] and we use largest value in no heat input as the upper shelf and smallest value in as 87kJ/cm heat input as the lower shelf.

$$vE(J) = \frac{vE_{us} - vE_{ls}}{\exp\{-a(J - vJ_E)\} + 1} + vE_{ls} \quad \cdots(4)$$

J : CO_2 equivalent heat-input (kJ/cm)

vE_{us} : Upper shelf (J)

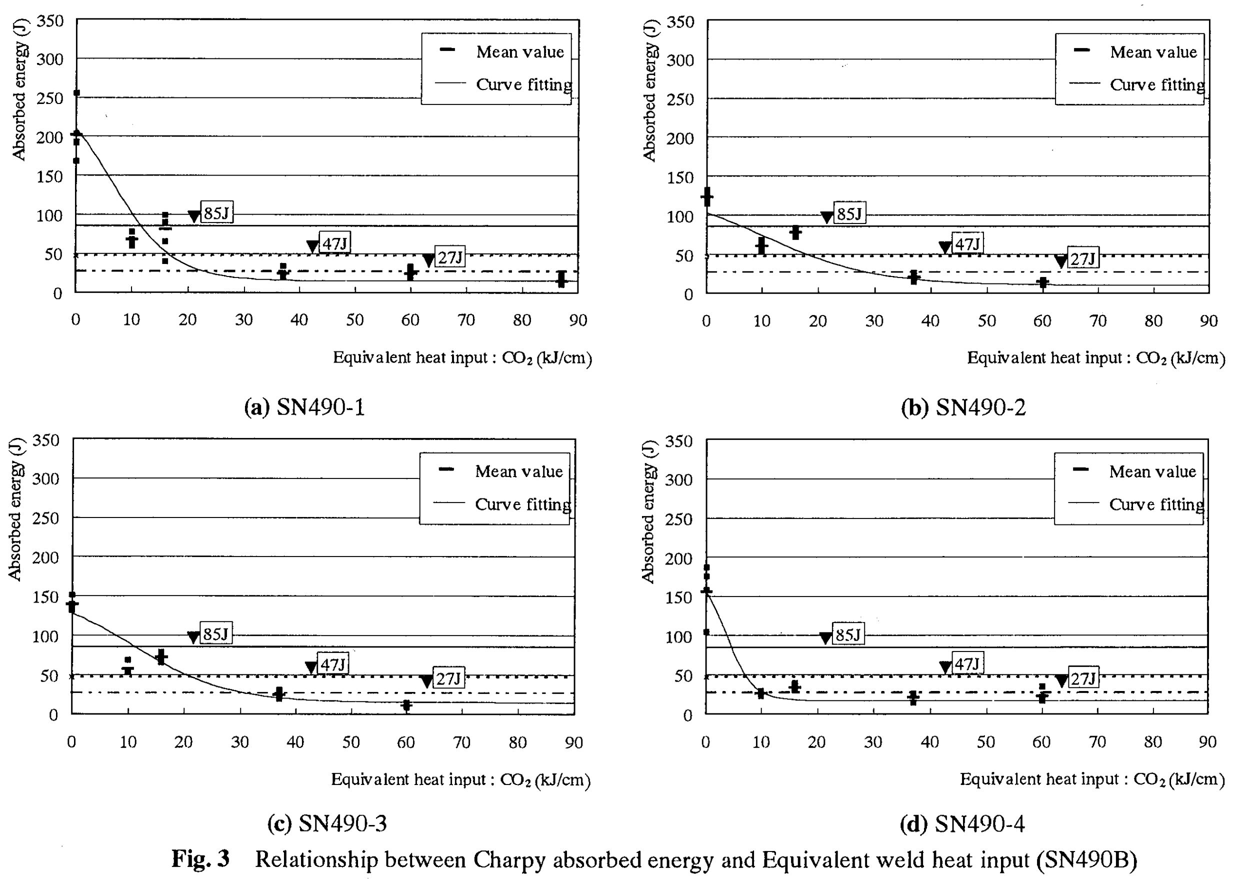
vE_{ls} : Lower shelf (J)

a, vJ_E : Fitting variables

3.1.1 Toughness decrease of SN400Bs 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 SN400B tends to decrease in all series. But decreasing rates are different in each series.

The SN400-1 and the SN400-2 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 SN400-1, after equivalent heat is inputted, the means of absorbed energy gradually decrease to 85J in about 37kJ/cm and decrease to 47J in about 60kJ/cm. For large equivalent heat-inputs, about 87kJ/cm, it decreases to 27J, that required for the base metal in the SN400B. In the case of the SN400-2, decrease of the means of absorbed energy become more gradual and the means never decrease blow 47J and 27J, even at an equivalent heat-input 87kJ/cm. From the above results, it could be said that the SN400Bs, which have more than



(a) SN490-1 (b) SN490-2

(c) SN490-3 (d) SN490-4

Fig. 3 Relationship between Charpy absorbed energy and Equivalent weld heat input (SN490B)

200J Charpy absorbed energy in no heat-input, can meet 85kJ at least until 37kJ/cm, can meet 47kJ at least until 60kJ/cm and can meet 27kJ at least until 87kJ/cm.

On the other hand, the SN400-3 has a small Charpy absorbed energy (56J), less than 85J in no heat-input. After equivalent heat is inputed, the means of absorbed energy decrease to under 45J in about 10kJ/cm and decrease to below 27J in about 16kJ/cm. It could be said that the SN400Bs, which have small Charpy absorbed energies, less than 85J in no heat-input, can't meet 27kJ even in small equivalent heat-input.

3.1.2 Toughness decrease of SN490Bs by welding heat-input

With decreasing equivalent welding heat-input, the Charpy absorbed energy of the SN490Bs also tends to decrease significantly in all series. Differed from the SN400B, difference in each series is relatively similar in the SN490B.

All series of the SN490B have large absorbed energies, much more than 85J with no heat-input. In the case of the SN490-1, the SN490-2 and the SN490-3, after equivalent heat is inputted, the means of absorbed energy gradually decrease to 85J in about 10kJ/cm, decrease to 47J in about 16kJ/cm and decrease to 27J in about 37kJ/cm or less. Only in the case of the SN400-4, the means of absorbed energy decrease significantly and the means never decrease to about 27J in equivalent input 10kJ/cm and 16kJ/cm, even though the absorbed energy for no heat-input are larger than the SN490-2 and the SN490-3. The tensile test results and the chemical compositions of the SN490-4 do not show big differences compared to the SN490-1～ SN490-3.

From the above results, it could be said that the SN490B, which have more than 85J Charpy absorbed energy for no heat-input, can not meet 27kJ in heat-input 37kJ/cm. At heat-input 16kJ/cm, most of the SN490Bs can meet 27J and 47J, but some of the SN490Bs cannot meet 47kJ in very small heat-input, 10kJ/cm. And almost of the SN490B cannot meet 85J in very small heat-input, 10kJ/cm.

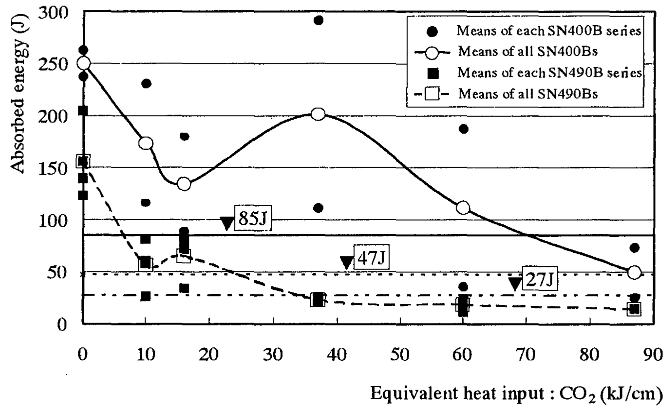


Fig.4 Comparison between SN400Bs and SN490Bs

3.1.3 Comparison between SN400Bs and SN490Bs

Fig.4 shows the means of Charpy absorbed energy for every equivalent welding heat-input. The SN400-3 is avoided because the Charpy absorbed energy is small compared to the others. Means of all SN400Bs and SN490Bs are also shown in Fig.4.

Not only in no heat-input, in all welding heat-input the means of the absorbed energy of the SN400Bs are larger than those of SN490Bs. The decreased rates of the absorbed energy of the SN400Bs are also smaller than that of SN490Bs.

Therefore, it could be said that the SN400B can meet larger Charpy absorbed energy at all heat-inputs than the SN490B and the SN400B can meet large its toughness at higher heat-input compared to the SN490B.

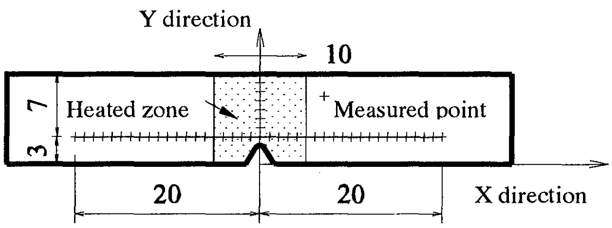
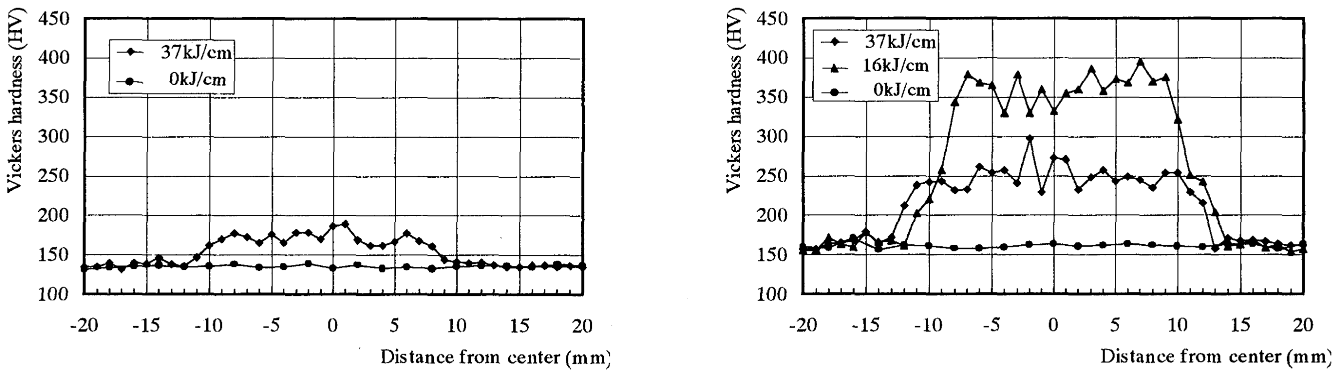


Fig.5 Measured points of Vickers hardness test



(a) SN400-3 (b) SN490-3

Fig. 6 Relationshp between Charpy absorbed energy and Equivalent heat input (SN400B)

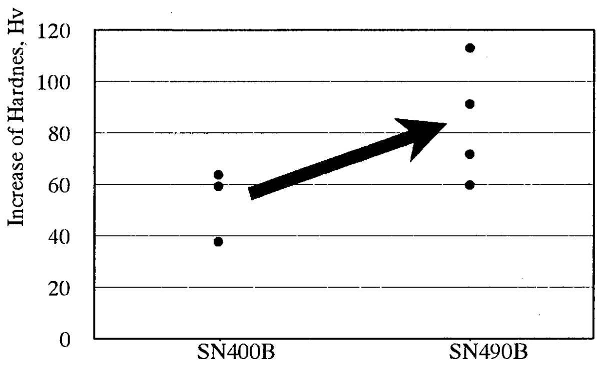


Fig.7 Comparison of the Vickers hardness tests results between SN400B and SN490B (Heat input = 37J/cm)

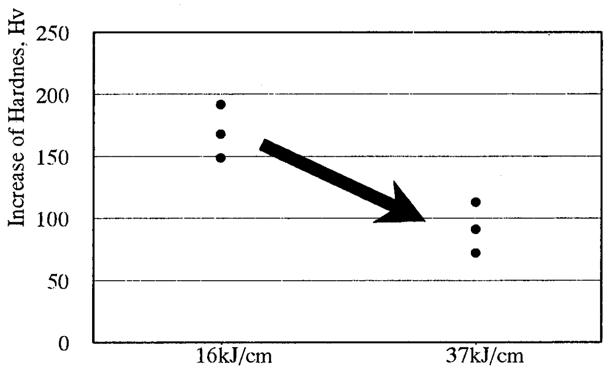


Fig.8 Comparison of the Vickers hardness tests results between heat input 16kJ/cm and 37kJ/cm (SN490B)

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 1mm from the center to +20mm and –20mm of X-direction. Measured points of the heat-input specimen are shown in **Fig.5**. **Fig.6** shows the example of the Vickers hardness test results.

Fig.7 shows the comparison of the Vickers hardness tests results between the SN400Bs and the SN490Bs at heat-input 37J/cm. The increased values of the Vickers hardness in Fig.7 are the means from –6mm to +6mm of X-direction. The Vickers hardness values of the SN490Bs were larger than those of the SN400Bs for no heat-input, but differences were not so large, about 10 ~ 20HV. After the welding heat-input, increases of hardness of the SN490Bs were much larger than those of the SN400Bs. So increase of hardness is related to toughness at the same heat-input. It could be said that the steel grade, which becomes harder for the same welding heat-input than the other steel grades, has smaller absorbed energy and smaller limit of heat-input.

Fg.8 shows the comparison of the Vickers hardness tests results between heat-input 16kJ/cm and 37kJ/cm in the SN490Bs. The increases in values of the Vickers hardness in Fig.8 are also means from –6mm to +6mm of X-direction. The increased values of the SN490Bs for heat-input 37kJ/cm were smaller than those for 16kJ/cm. It could be said that in the same steel grade, the increase in values of hardness with welding heat-input become small but absorbed energies also become small with increasing of equivalent heat-input.

3.3 Microstructures after welding heat-input

Fig.9 and **Fig.10** show photos of the microstructures of the SN400Bs and the SN490Bs for a welding heat-input 37kJ/cm. These are typical of the each steel grade, but the large differences are not observed in each grade.

The microstructures of the SN400Bs consist mainly of martensite, but ferrite was observed at the grain boundary. On the other hand, the microstructures of the SN490Bs consist of martensite and ferrite was not

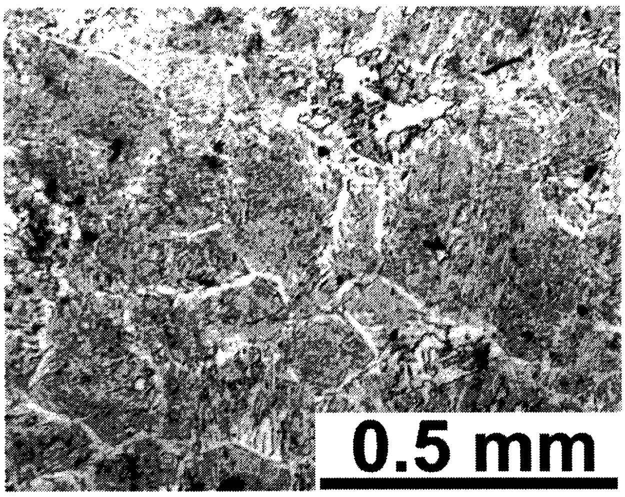


Fig.9 Microstructures of SN400B (SN400-2, welding heat-input 37kJ/cm)

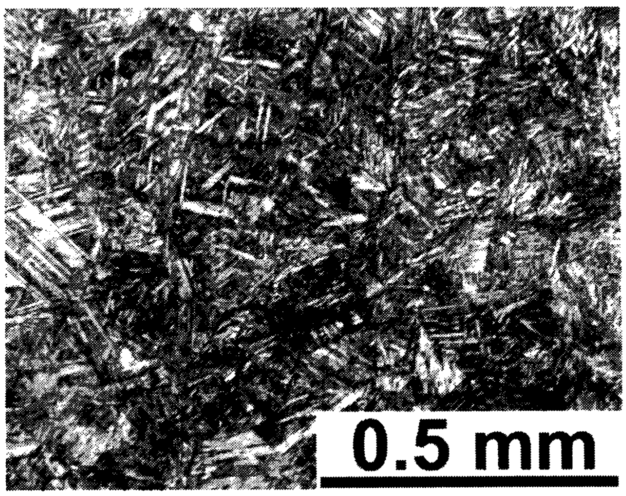


Fig.10 Microstructures of SN490B (SN490-2, welding heat-input 37kJ/cm)

observed. The difference of this martensitization rate might be caused by the difference of the equivalent carbon. And it seems that the difference of martensitization rate causes the difference of toughness decrease and the hardness between the SN400B and the SN490B.

4. Conclusions

In this paper, the relationship between the toughness of simulated CGHAZs of the rolled steels for building structure and the welding heat-input limit are investigated.

The investigation results are summarized as follows.

(1) The SN400B can meet higher Charpy absorbed energy at all heat-input compared with the SN490B and the SN400B can meet its large toughness at higher heat-inputs compared with the SN490B. This difference might be caused by the difference of martensitization rate of the SN400B and 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. But in the case of the SN400B, which has a small Charpy absorbed energy, less than 85J for no heat-input, can't meet all the required toughnesses even at small equivalent heat-input.

(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.

Determination of the required toughness value, which includes the effect of the toughness mismatch, of CGHAZs to avoid the general yield brittle fracture and more experimental results will be required in future researches.

Acknowledgments

The author would like to thank Mr. HORINOUCH T., Mr. MAEDA M., Mr. NAKADE I. and Dr. TAKAHASHI M. for their help during the experiments. This study was financially supported in part by the Grant-in-Aid for Encouragement Research (A) from the Ministry of Education, Culture, Sports, Science and Technology.

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