

Title	Cooling Time Parameter and Hardenability Estimation of HAZ in Welding of Medium, High Carbon Machine Structural Steels : Toughness Improvement of the HAZ for Macine Structural Carbon and Low Alloy Steels (Report 3) (Mechanics, Strength & Structural Design)
Author(s)	Matsuda, Fukuhisa; Liu, Wu Shyuan
Citation	Transactions of JWRI. 1990, 19(2), p. 207-214
Version Type	VoR
URL	https://doi.org/10.18910/4857
rights	
Note	

Osaka University Knowledge Archive : OUKA

<https://ir.library.osaka-u.ac.jp/>

Osaka University

Cooling Time Parameter and Hardenability Estimation of HAZ in Welding of Medium, High Carbon Machine Structural Steels

Toughness Improvement of the HAZ for Machine Structural Carbon and Low Alloy Steels
(Report 3)[†]

Fukuhisa MATSUDA*, and Wu Shyuan LIU**

Abstract

Hardenability is one of the important factors for estimating weldability of steels, therefore the cooling time parameter ($\Delta t_{8/5}$) was usually used for estimating the microstructure and hardenability of lower carbon steels.

However it is not clear whether the parameter of $\Delta t_{8/5}$ is suitable or not for higher carbon steels.

Therefore this paper has been investigated the suitable cooling time for these steels using a Gleeble tester. Furthermore by use of new cooling parameter ($\Delta t_{8/3}$) and carbon equivalent estimation equation on hardenability has been obtained.

Main conclusions obtained are as follows:

(1) The cooling time parameter of $\Delta t_{8/3}$ is better than that of $\Delta t_{8/5}$ for estimating the hardenability on the HAZ of higher carbon steels, whose carbon content is more than 0.3%.

(2) The hardness of the HAZ of medium and high carbon ($C \geq 0.3\%$) machine structural steels could be predicted within 15% deviation by using the introduced equation in combination of $\Delta t_{8/3}$ and carbon equivalent.

KEY WORDS: (Heat-affected zone) (Cooling time) (Hardenability) (Medium, high carbon machine structural steels) (Proposal)

1. Introduction

It is well-known that hardenability of HAZ is one of the important factors for estimating weldability of steels. Therefore the Parameter of cooling time from 800 to 500°C ($\Delta t_{8/5}$) has been usually used for estimation of the hardenability of low carbon high strength steels so far.

However it was not clear if $\Delta t_{8/5}$ is also useful parameter for the estimation for higher carbon steels, because the M_s temperature of these steels is lower than usual low carbon steels.

For this purpose, this paper has been investigated the usefulness of application of $\Delta t_{8/3}$ parameter for the HAZ of higher carbon steels.

Conclusively, it was cleared that the $\Delta t_{8/3}$ parameter is better than $\Delta t_{8/5}$ for these steels. Then the authors have introduced a new equation for estimation of the hardenability on the HAZ for higher carbon steels using $\Delta t_{8/3}$ parameter and carbon equivalent.

2. Experimental Procedures

2.1 Steels used

Medium, high carbon steel bars of JIS S25C, S35C, S40C, S55C, SKV70, SK5, SK3 and Medium, high carbon low alloy steel bars of JIS SC,440, SUJ2, SCM435,445, SNCM420,439,447 were used as base metal. All of these are commercial steel bars whose chemical compositions are given in **Table 1**.

2.2 Experimental procedures

The shape and size of the simulated round bar specimen is 10 mm diam. and 55 mm in length with a circle notch in the center of the length which is same as shown in the previous report¹⁾.

Simulated thermal cycle is given by a dynamic testing machine (Gleeble 1500) which is based on resistance heating. The cooling time parameters are defined as $\Delta t_{8/5}$, from 800 to 500°C, and $\Delta t_{8/3}$, from 800 to 300°C. Lower and Upper cooling times of $\Delta t_{8/3}$ for the given $\Delta t_{8/5}$ are shown in Fig. 2, the reason of which will be shown in 3.1 In this research the given $\Delta t_{8/5}$ were

[†] Received on November 5, 1990

* Professor

** Graduate Student

Transactions of JWRI is published by Welding Research Institute of Osaka University, Ibaraki, Osaka 567, Japan

Table 1 Chemical compositions of steels used*

Designation	steel	Chemical Composition (wt. %)									
		C	Si	Mn	P	S	Ni	Cr	Mo	N	O
Carbon steels	S25C	0.24	0.20	0.39	0.018	0.018	0.04	0.04	0.01	—	—
	S35C	0.33	0.24	0.69	0.018	0.018	0.02	0.03	0.01	—	—
	S40C	0.39	0.25	0.70	0.026	0.028	0.02	0.12	0.01	—	—
	S55C	0.54	0.26	0.69	0.022	0.011	0.05	0.19	0.02	—	—
	SKV70	0.72	0.22	0.75	0.025	0.023	0.07	0.22	0.01	0.0096	0.002
	SK5	0.89	0.24	0.29	0.022	0.020	0.04	0.12	—	0.0043	0.001
C _r steels	SK3	1.05	0.33	0.98	0.020	0.018	0.05	0.47	—	0.0130	0.001
	SC _r 440	0.40	0.29	0.76	0.025	0.012	0.07	1.09	0.02	0.0120	0.004
C _r -M _o steels	SUJ2	0.96	0.26	0.46	0.015	0.009	0.05	1.46	0.01	0.0073	0.001
	SCM 435	0.36	0.23	0.80	0.022	0.013	0.10	1.11	0.15	—	—
N _i -C _r -M _o steels	SCM 445	0.45	0.24	0.78	0.017	0.018	0.07	1.07	0.15	0.0140	0.001
	SNCM420	0.21	0.24	0.61	0.020	0.011	1.61	0.46	0.21	—	—
	SNCM439	0.39	0.28	0.73	0.012	0.007	1.72	0.69	0.17	0.0094	0.003
	SNCM447	0.48	0.26	0.81	0.025	0.012	1.65	0.72	0.15	—	—

* As received base metal.

adopted for 3.5, 6, 21, 50, and 100 sec for which $\Delta t_{8/3}$ were individually varied from 9.7 to 13.7, from 17 to 28, from 70 to 135, from 187 to 310 and from 280 to 400 sec. Moreover additional $\Delta t_{8/3}$ was tried to extend to 2500 sec in order to introduce the equation on hardenability of the HAZ.

3. Experimental Results and Discussions

3.1 Selection for parameter of cooling time

Fig. 1 shows the relationship between $\Delta t_{8/5}$ and hardness for continuous cooling simulated HAZ for each steel used. Generally, increasing $\Delta t_{8/5}$ shows a decrease in hardness in each steel, although the variation of hardness is larger in higher carbon steel as the hardness of martensite is higher in higher carbon steel. It is estimated that between 3.5 and about 30 sec of $\Delta t_{8/5}$, there is a big microstructural change from martensite to fully ferritic-pearlitic or bainitic structures.

In Fig. 1, there is a dotted line which is calculated from Okumura's equation²⁾ using chemical composition of JIS S55C in Table 1. As a result, the data of dotted line are lower than this investigated data of S55C on hardness in these cooling time range. Especially, the difference is fair in the range of about $\Delta t_{8/5}$: 6~21 sec, and is not remarkable at $\Delta t_{8/5}$: 3.5 sec and more than 50 sec.

The authors have investigated the reason why there is a difference so much.

Using Inagaki's monographs³⁾ the authors calculated both $\Delta t_{8/5}$ and $\Delta t_{8/3}$ for actually used welding conditions (weld heat input 9~63 KJ/cm, preheating less than 573 K, plate thickness 12~34 mm) for SAW and

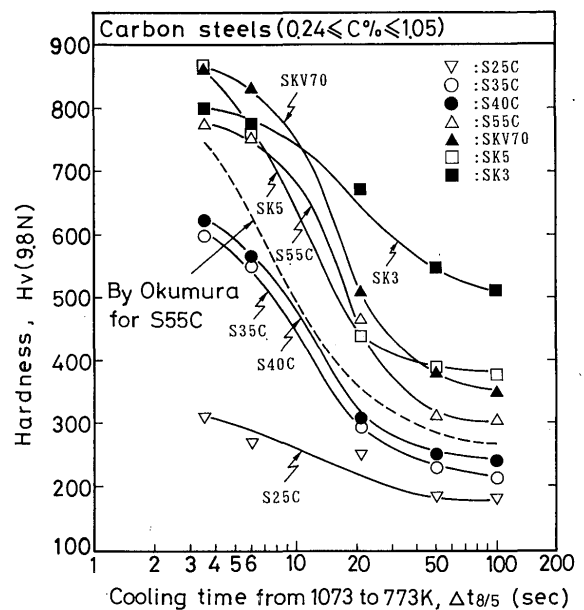


Fig. 1 Effect of cooling time ($\Delta t_{8/5}$) on hardness.

SMAW. Fig. 2 shows the relationship between $\Delta t_{8/5}$ and $\Delta t_{8/3}$ in the measured results. As a result, $\Delta t_{8/3}$ is shown in between two lines of lower and upper cooling time with each $\Delta t_{8/5}$. Generally, increasing $\Delta t_{8/5}$ shows an increase in difference of $\Delta t_{8/3}$, for example, the difference is about 65 sec for 21 sec of $\Delta t_{8/5}$ and about 123 sec for 50 sec. Therefore, even at same $\Delta t_{8/5}$, the cooling time from 500 to 300°C ($\Delta t_{5/3}$) is much different depending on changing heat input, preheating temperature or plate thickness.

Fig. 3 shows the hardness change against $\Delta t_{8/5}$ at $\Delta t_{8/5}$: 3.5, 6, 21, 50 and 100 sec with various $\Delta t_{8/3}$ in S35C, S55C, SKV70. Now, compare the hardness

difference between lower cooling time (solid mark) and upper cooling time (open mark) at each $\Delta t_{8/5}$ of 3.5, 6, 21, 50, 100 sec. In the shortest cooling time of $\Delta t_{8/5}$: 3.5 sec, there is no difference in hardness between solid and open mark in each steel, the structure of which was almost full martensite in despite of variation of $\Delta t_{8/3}$. Moreover, in the longest cooling time of $\Delta t_{8/5}$ in each steel (S35C: 21 sec, S55C: 50 sec, SKV70:50 sec) there is also no difference in hardness in each steel, the structure of which was almost mixture

of ferrite and pearlite. However, in the intermediate $\Delta t_{8/5}$ between them, there is a remarkable difference in hardness in each steel between solid and open mark. In these $\Delta t_{8/5}$, the ratios of martensite and bainitic structure were different in depending on the difference of $\Delta t_{5/3}$, that is open and solid mark, even at same $\Delta t_{8/5}$.

The relationship for $\Delta t_{8/5}$ and the hardness difference (ΔH_V) between lower and upper cooling time of $\Delta t_{8/5}$ in S25C, S35C, S55C and SKV70 is shown in Fig. 4. As a result, the maximum hardness difference increases with C content. Moreover, the maximum hardness shows at $\Delta t_{8/5}$: 6 to 8 sec in S25C and S35C, at 10 sec in S55C and at 21 sec in SKV70.

Fig. 5 shows a microstructural change of SKV70 at $\Delta t_{8/5}$: 21 sec, in which (a) shows 70 sec and (b) 135 sec for $\Delta t_{8/3}$. In Fig. 5 (a) there is about 50% martensite

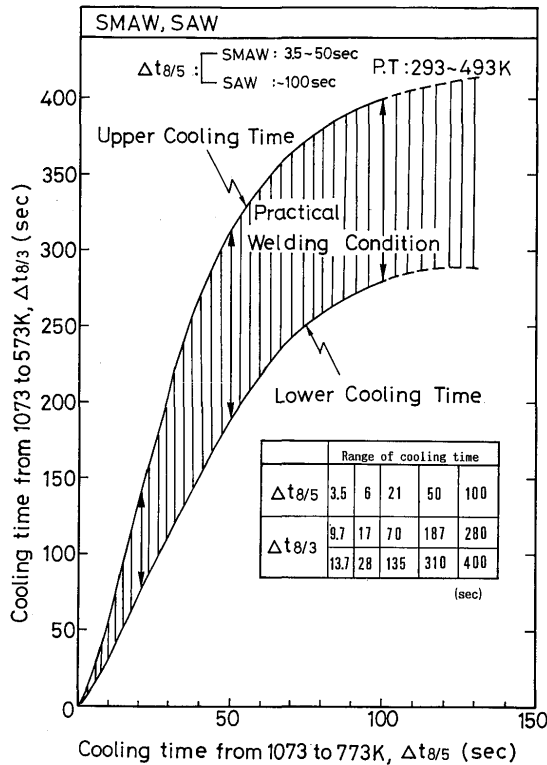


Fig. 2 Relationship between $\Delta t_{8/5}$ and $\Delta t_{8/3}$ in actual welding operation.

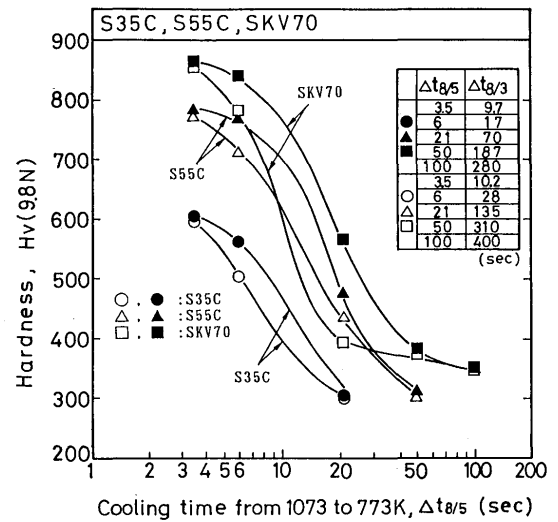


Fig. 3 Effect of cooling time of $\Delta t_{8/3}$ on hardness at given $\Delta t_{8/5}$.

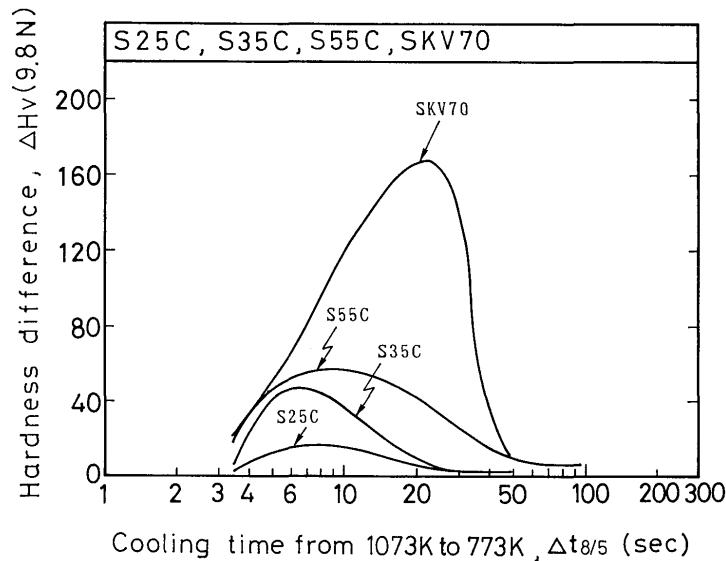
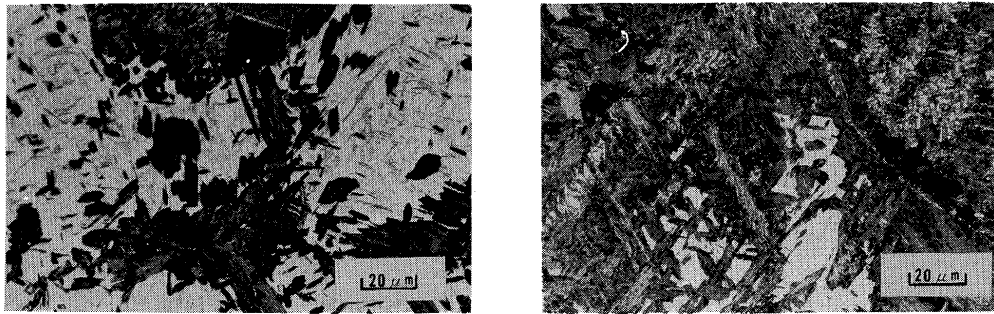


Fig. 4 Effect of cooling time of $\Delta t_{8/3}$ on hardness difference (ΔH_V) at given $\Delta t_{8/5}$.



(a) $\Delta t_{8/5}$: 21
 $\Delta t_{8/3}$: 70 (sec)

(b) $\Delta t_{8/5}$: 21
 $\Delta t_{8/3}$: 135 (sec)

SKV70

Fig. 5 Microstructural change of SKV70 at 70 and 135sec of $\Delta t_{8/3}$ at $\Delta t_{8/5}$: 21sec.

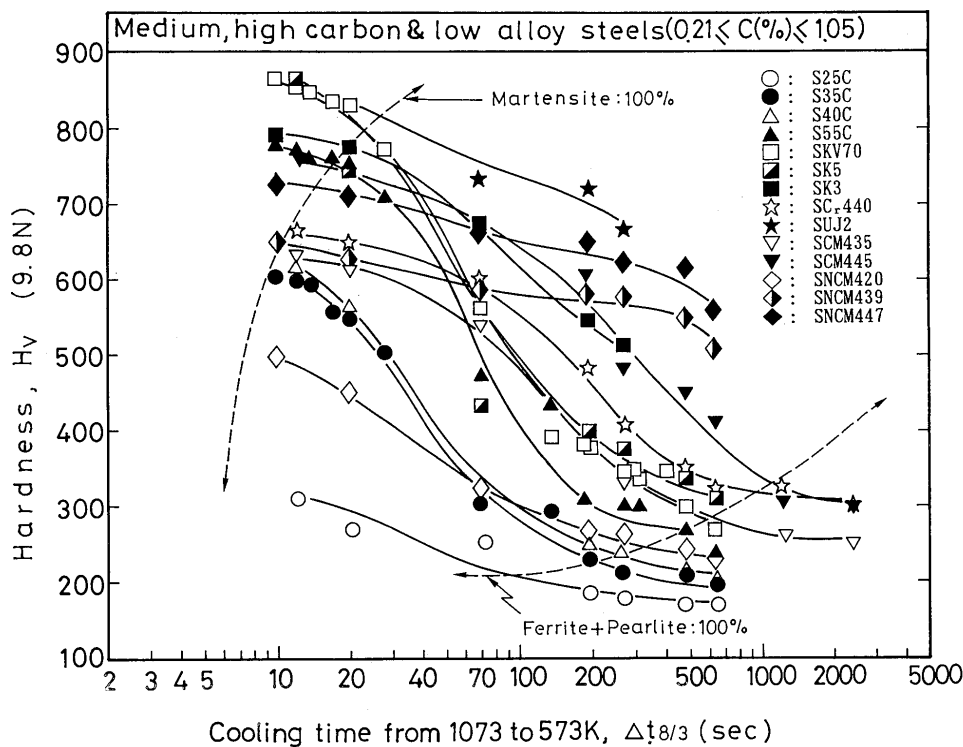


Fig. 6 Relationship between $\Delta t_{8/3}$ and hardness of medium, high carbon and low alloy steels.

and 50% bainite and pearlite, but, in Fig. 5 (b) there is only about 15% martensite and 85% bainite and pearlite. Therefore, within the actual welding operation the microstructure and hardness were changed by varying $\Delta t_{5/3}$, even at same $\Delta t_{8/5}$ in these steels.

3.2 Proposal of estimation equation on hardenability

In section 3.1, the authors confirmed that the $\Delta t_{8/3}$ parameter is better than $\Delta t_{8/5}$ for the estimation of the hardenability on HAZ for plain medium and high carbon steels. Then the authors have introduced in this section an estimation equation for general medium

and high carbon machine structural steels including C_r , M_o and N_i alloying elements in low level, using the concept of $\Delta t_{8/3}$ parameter and carbon equivalent.

3.2.1 Estimated result of hardenability

Fig. 6 shows the relationship between $\Delta t_{8/3}$ (12, 20, 71, 195, 270, 480, 640, 1280 and 2440 sec) and hardness for continuous cooling simulated HAZ in medium, high carbon and low alloy steels ($0.21 \leq C\% \leq 1.05$).

Generally, increasing in $\Delta t_{8/3}$ shows a decrease in hardness in each steel, and there is a remarkable decrease in hardness more than 20 sec in carbon steels.

However, in comparison with the result of carbon steels, the decreasing in hardness is not remarkable in low alloying steels, especially, in SNCM439, 447 and SUJ2, of the additions of about $0.7C_r$ and $1.7\% N_r$, and $1.5C_r$ ⁴⁾, then the decreasing in hardness with continuous cooling method is difficult within actual range of welding heat input.

As a result of microscopic investigation of the structural change, in the left side of the figure, dotted line shows the maximum cooling time in order to show 100% martensitic structure, and in the right side, the other dotted line shows the minimum cooling time in order to show 0% bainitic structure, namely, 100% ferritic and pearlitic structure in these steels. However, in SNCM439, 447 and SUJ2 the minimum cooling time of 100% ferritic and pearlitic structure was estimated by CCT diagrams which were measured⁵⁾.

3.2.2 Introduction for estimation equation on hardenability

From Fig. 6 the authors have simply estimated that the relationship between hardness (H_V) and cooling time ($\Delta t_{8/3}$) is as Fig. 7. As a result, the shape of curve for the relationship between H_V and $\Delta t_{8/3}$ could be

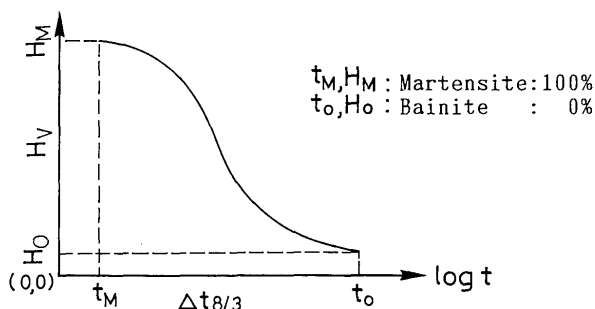


Fig. 7 Shape of essential curve between 100% martensite and 0% bainite.

shown as following equation closely²⁾:

$$H_V = A \cdot \tan^{-1} \Delta t_{8/3} + B \quad (1)$$

Here, A and B are constants.

Now if the parameters of hardnesses of 100% martensite (H_M) and 0% bainite (H_0) and the cooling times of 100% martensite (t_M) and 0% bainite (t_0) could be introduced, the equation (1) will be converted to equation (2) using four parameters (H_M , H_0 , t_M and t_0):

$$H_V = (H_M + H_0)/2 + (H_M - H_0)/2 \times \tan^{-1} [(2 \log \Delta t_{8/3} - \log t_0 - \log t_M)/2] / \tan^{-1} [(\log t_M - \log t_0)/2] \quad (2)$$

Here, the unit of cooling time is shown by logarithm.

Therefore, the relationships between four parameters (H_M , t_M , H_0 , t_0) and chemical composition have been individually measured by computer analysis as the following:

(A) 100% martensitic Hardness, H_M

Generally, the hardness of 100% martensite is generally said that it is decided by only C content. The results of the authors measurements well agree with those of Okumura²⁾. The relationship between hardness and C carbon is shown in Fig. 8. Mark \circ show the data of plain carbon steels, and \bullet show the data of low alloying steels. Therefore, the equation on the relationship between H_M hardness and C content is shown in equation (3):

$$H_M = 1265C - 182C^2 - 466C^3 - 10C^4 + 218 \quad (3)$$

(B) Maximum cooling time for 100% martensite, t_M

The relationships between cooling time, $\log t_M$, and carbon equivalent I for t_M , $C_{eq} I (t_M)$, in multiple re-

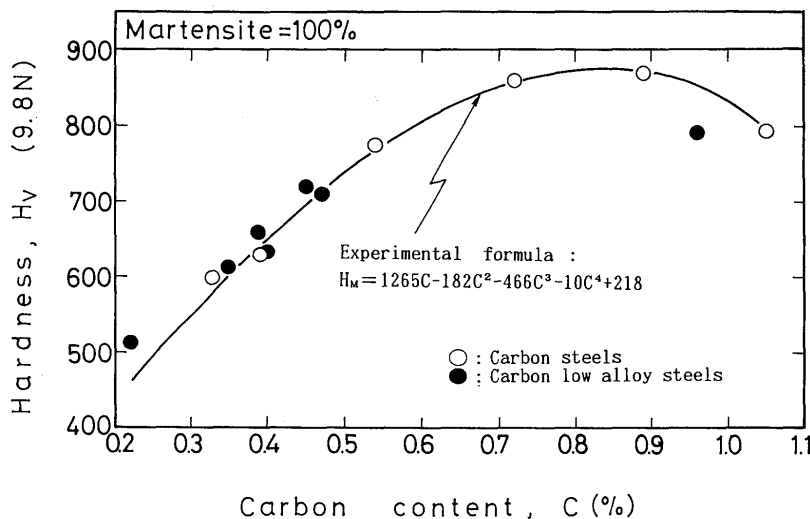


Fig. 8 Relationship between carbon content and hardness on 100% martensite.

gression analysis are shown in equation (4) and (5):

$$\log t_M = 0.48C_{eq} I(t_M) + 0.2 \quad (4)$$

$$\text{Here, } C_{eq} I(t_M) = C + M_n + (2)S_i + (1/10)N_i + (4/5)C_r + (1/5)M_o \quad (5)$$

Moreover, Fig. 9 show relationship between estimated and experimental value of maximum cooling time for 100% martensite in regression analysis with equation (4) and (5), where the coherency which is represented by the square of correlation coefficient (R^2) is 0.93.

(C) 100% ferrite and pearlite hardness, H_o

The relationships between H_o and suitable carbon equivalent, $C_{eq} II(H_o)$, are represented by multiple regression analysis, which are shown in equations (6) and (7):

$$H_o = 173C_{eq} II(H_o) + 140 \quad (6)$$

$$\text{Here, } C_{eq} II(H_o) = C + (1/33)M_n + (1/14)S_i + (1/20)N_i + (1/4)C_r + (8/5)M_o \quad (7)$$

Moreover, Fig. 10 shows the relationship between estimated and experimental value of hardness (H_o) on 100% ferrite and pearlite structure in regression analysis with equation (6) and (7), where the square of correlation coefficient (R^2) is 0.92.

(D) Minimum cooling time for 100% ferrite and pearlite, t_o

The relationships between cooling time, $\log t_o$, and

carbon equivalent $C_{eq} III(t_o)$ in multiple regression analysis are shown in equation (8) and (9):

$$\log t_o = 0.8C_{eq} III(t_o) + 1.57 \quad (8)$$

$$\text{Here, } C_{eq} III(t_o) = C + (1/4)M_n + (3/4)S_i + (2/5)N_i + (11/10)C_r + (2/5)M_o \quad (9)$$

Moreover, Fig. 11 shows the relationship between

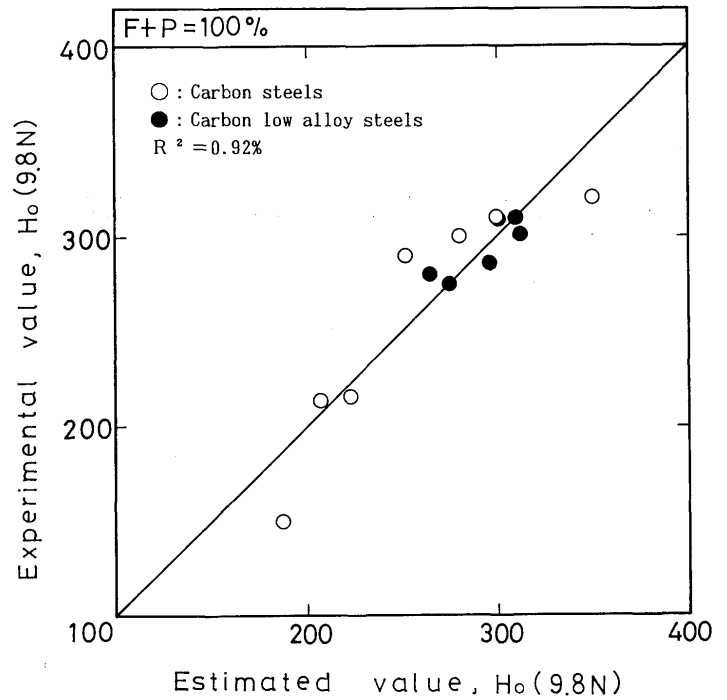


Fig. 10 Comparison of estimated value and experimental value of hardness on 100% F+P (ferrite+pearlite).

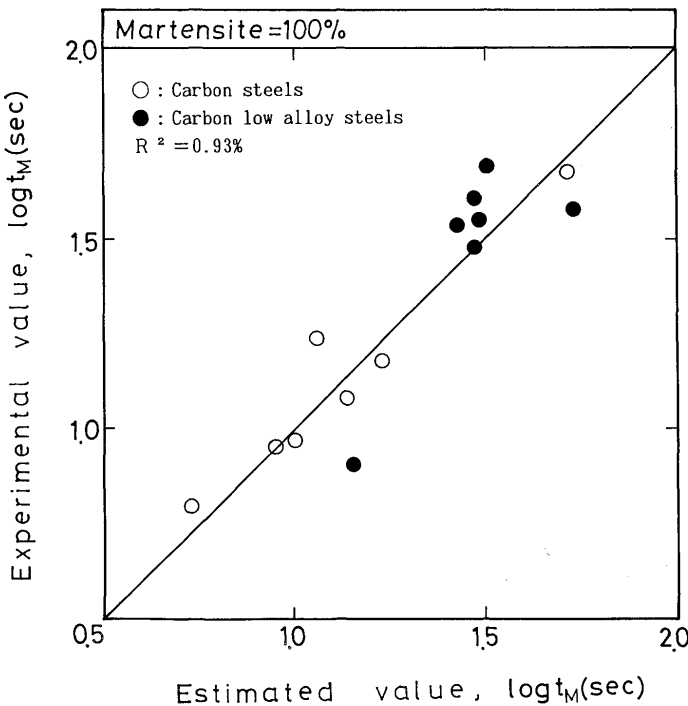


Fig. 9 Comparison of estimated value and experimental value of cooling time on 100% martensite.

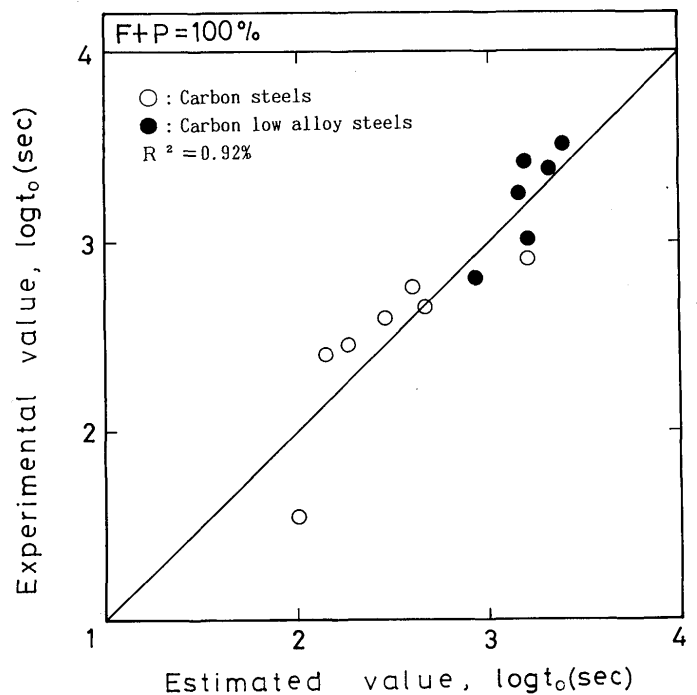


Fig. 11 Comparison of estimated value and experimental value of cooling time on 100% F+P (ferrite+pearlite).

estimated and experimental value of cooling time ($\log t_0$) for 100% ferrite and pearlite structure in regression analysis with equation (8) and (9), where the square of correlation coefficient (R^2) is 0.92.

3.2.3 Proposal for the equation on hardenability estimation

There are well characteristic equations represented by computer analysis of about more than 0.92 correlation coefficient obtained in section 3.2.2.

Substitution of the equations (3), (4), (5), (6), (7), (8) and (9) into equation (2), introduces equation (10), which can estimate the hardenability of the HAZ in welding of medium, high carbon machine structural steels. That is;

$$H_v = (633C - 91C^2 - 233C^3 - 5C^4 + 178.8 + 86.5C_{eq} \text{ II}(H_0)) + (633C - 91C^2 - 233C^3 - 5C^4 + 39.2 - 86.5C_{eq} \text{ II}(H_0)) \times \tan^{-1}(\log t_{8/3} - 0.24C_{eq} \text{ I}(t_M) - 0.4C_{eq} \text{ III}(t_0) - 0.89) / \tan^{-1}(0.24C_{eq} \text{ I}(t_M) - 0.4C_{eq} \text{ III}(t_0)) \quad (10)$$

where, $0.21\% \leq C \leq 1.05\%$, $S_i \leq 0.33\%$, $M_n \leq 0.98\%$, $N_i \leq 1.72\%$, $C_r \leq 1.46\%$, $M_o \leq 0.21\%$.

Moreover, Fig. 12 shows the relationship between estimated and experimental value of hardness (H_v) with regression analysis on equation (10). As a result,

a part of estimated values with * mark are detached from range within 15% of experimental value, that the steels of which are S25C and SNCM420 with 0.24 and 0.21% C.

Therefore, the equation (10) seems to be valuable for medium, high carbon machine structural steels of carbon content more than 0.3%.

4. Conclusions

In order to estimate the hardenability of HAZ in welding of medium and high carbon machine structural steels (0.2 to 1.05% C), this paper has treated the selection for the parameter of cooling time and the proposal of estimation equation on hardenability of the HAZ using the parameter of cooling time and carbon equivalents. These experiments were done using Gleeble 1500.

Main conclusions obtained are as follows:

- (1) The cooling time parameter of $\Delta t_{8/5}$ has been used so far, for estimation of hardenability of HAZ for conventional low carbon high strength steels. However, in steels of carbon content more than 0.3% the cooling time parameter of $\Delta t_{8/3}$ was better for use to evaluate the hardenability.

Because the hardness was a little differential depending on cooling time below 500°C. Moreover, the hardness difference was increased with increas-

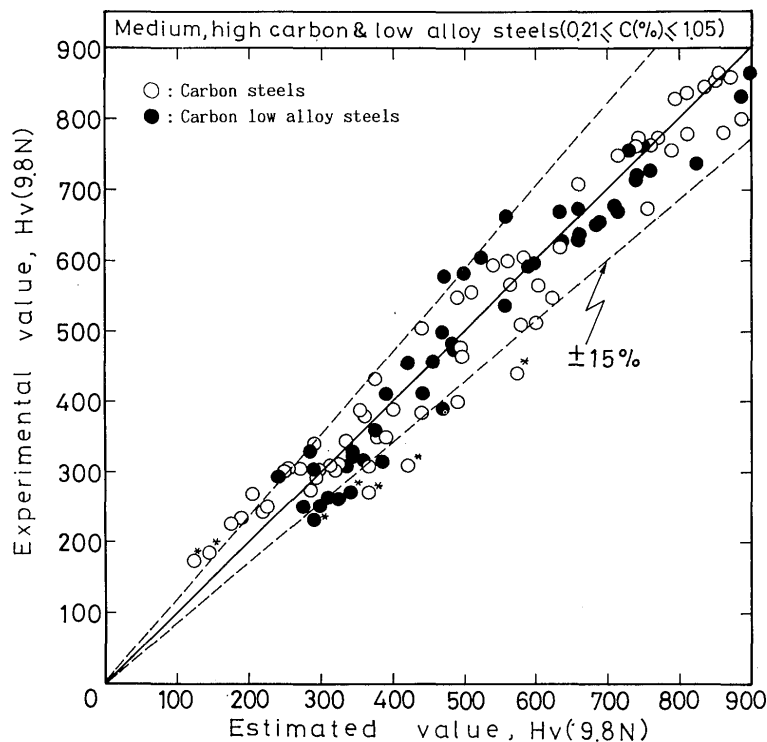


Fig. 12 Relationship between estimated and experimental hardness on the estimation equation for medium, high carbon and low alloy steels.

ing carbon content.

- (2) For these steels the hardnesses of 100% martensite (H_M) and 100% ferrite+pearlite structures (H_O), and the maximum cooling time for 100% martensite (t_M) and the minimum cooling time for 100% ferrite+pearlite structures (t_O) have been estimated by individual carbon equivalent using multiple regression analysis. The estimated equation well agree with the experiimetal values.
- (3) With an use of parameters of H_M , H_O , t_M and t_O the hardenability estimation was tried for these steels. The essential equation used are as follows;

$$H_V = (H_M + H_O)/2 + (H_M - H_O)/2 \\ \times \tan^{-1}[(2 \log 4t_{8/3} - \log t_O - \log t_M)/2] / \\ \tan^{-1}[(\log t_M - \log t_O)/2]$$

- (4) As a result, the equation (10) was obtained as an estimation equation. The relationship between estimated and experimental value on hardness in

these steels was a good agreement within $\pm 15\%$ except steels of 0.21%. Therefore, the authors have proposed here that the equation (10) is available as the estimation equation of hardenability of the HAZ for steels as $0.30\% \leq C \leq 1.05\%$, $S_i \leq 0.33\%$, $M_n \leq 0.98\%$, $N_i \leq 1.72\%$, $C_r \leq 1.46\%$, $M_o \leq 0.21\%$.

References

- 1) Matsuda et al: Toughness Improvement of the HAZ for Machine Structural Carbon and Low Alloys Steels (Report 1), Transactions of JWRI, Vol. 18, No. 2, 1989, P. 79.
- 2) Okumura: Effects of elements on the hardenability and cold crack susceptibility of HAZ of constructional steel weldments, Ph D thesis of Osaka University 1990, 6 (in Japanese).
- 3) Inagaki et al: Welding of high strength steels, 1965, cited from "Welding Metallurgy" edited by F. Matsuda, 1972, 4. (in Japanese).
- 4) Kasugai et al: Effect of Alloying Elements on Transformation Behavior in Synthetic Weld Heat-Affected Zone of Steels (V), J, Japan Weld. Soc., Vol. 44 No. 8 1975, P. 73 (in Japanese).
- 5) Japan Metal Soc: Metal Hand book, Maruzen, 1984, P. 400~404 (in Japanese).