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Weldability Concept on Hardness Prediction †

Yoshiaki ARATA*, Kimiyuki NISHIGUCHI**, Takayoshi OHJI*** and Naoki KOHSAI****

Abstract

The maximum hardness is adopted as an index symbolizing the weldability of steels. By newly introducing two parameters (cooling function f(τ) and alloy-element function f(E)) the fundamental equation for the maximum hardness is given. The empirical formula is obtained which is very useful in practice and shows a good agreement with many experimental data.

KEY WORDS: (Weldability) (Maximum Hardness) (Cooling Time) (Alloy-element) (Carbon Equivalent)

1. Introduction

The maximum hardness in the weld part of a metal is one of the most important parameter to estimate the occurrence of "low-temperature crack". The value of this parameter reflects a standardized base for the appropriate selection of the base metal and the welding condition to prevent the low-temperature crack. It is indeed an index symbolizing the "weldability" of a metal and will be formulated in the following expression.

$$H_v = F\{ f(\tau), f(E) \} + F_o , \qquad \ldots\ldots \quad [\mathrm{I}]$$

where $F\{f(\tau), f(E)\}$ shows a function of $f(\tau)$ and $f(E)$ which mean cooling function, alloy-element function, respectively and F_0 is numerical constant relating to basic hardness of a metal (a certain standard one).

Arata et al.[1] have attempted to solve this formula [I]. By using the carbon-equivalent C_{eq} for $f(E)$ and the cooling function $f(\tau_{T_1 \to T_2})$ for $f(\tau)$ during welding, the maximum hardness H_v is given by

$$H_v = F\{ f(\tau_{T_1 \to T_2}), C_{eq} \} + B , \qquad \ldots\ldots \quad (1)$$

where $\tau_{T_1 \to T_2}$ is the cooling time in seconds from a temperature T_1 to T_2 °C, and B is a numerical constant. T_1 and T_2 are selected to be the ones that characterize the important natures of steels; for example T_1=800°C and T_2=500°C. Assuming the function F in equation (1) to be the following relation

$$F = \frac{\mathrm{A}}{\tau^{K}_{T_1 \to T_2}} C_{eq} , \qquad \ldots\ldots \quad (2)$$

where A and K are numerical constants, equation (1) is written as follows by treating many experimental data.

$$H_v = \left\{ \frac{840}{\tau^{0.22}_{800 \to 500}} C_{eq} + 58 \right\} \pm 66 , \qquad \ldots\ldots \quad (3)$$

$$\text{where} \quad [C_{eq}] = [C] + \frac{[Mn]}{2.4} + \frac{[Si]}{24} + \frac{[Ni]}{14} + \frac{[Cr]}{16} + \frac{[Mo]}{60} ,$$

$$\tau_{800 \to 300} \risingdotseq 3.8 \times 10^{-2} \left[\frac{0.8 I_b V_b}{v_b h_p} \right] \left[\left(\frac{1}{(500 - T_0)^2} - \frac{1}{(800 - T_0)^2} \right] \right.$$

In this equation I_b, V_b, v_b, h_p and T_o are beam current [mA], beam voltage [kV], welding speed [cm/min], penetration depth [cm] and initial temperature of the specimen [°C], respectively. $[C]$, $[Mn]$, $[Si]$, $[Ni]$, $[Cr]$ and $[Mo]$ indicate weight percentages of each element in steels. The standard deviation σ were obtained experimentally to be 66 in the EB-weld part as given in the equation for the many kinds of steels such as carbon and

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* Professor

** Professor, Faculty of Engineering, Osaka University

*** Associate Professor, Faculty of Engineering, Osaka University

**** Mitsubishi Heavy Industry Co., Ltd.

low alloy steels. The result can be illustrated in **Fig. 1** and was confirmed for many kinds of electron beam welds of steels under various welding conditions.$^{2\text{-}3)}$ Such concept is known as Arata Electron beam weldability.$^{2)}$

In this paper the generalization of this weldability is intended to be applicable not only to EB welding but also to other welding methods. The maximum hardness is estimated quantitatively with a higher accuracy in the following way: several characteristic values obtained from welding CCT diagrams for many kinds of steels are treated statistically, and by using these values, F function in formula [I] is given by another form instead of equation (2). In this case attention is paid mainly to martensite structure region.

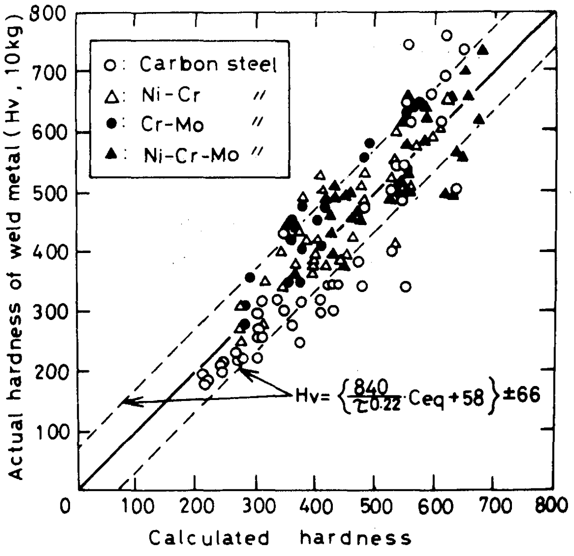


Fig. 1 Comparison of the actual hardness with the calculated hardness for EB-Welds of various steels using eq (3)

2. Formulation of the Problem

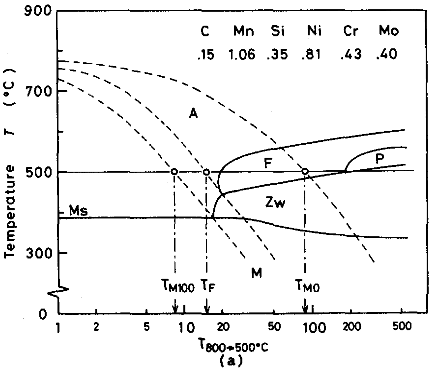
As is well known the maximum hardness of HAZ can be estimated$^{3)}$ from a welding CCT diagram (rapid heating with the maximum heating temperature of 1350°C). **Fig. 2** (a) is a CCT diagram of a typical high strength steel (HT-steel) and (b) shows the relation between the structure area percentage of constituent and the hardness obtained from (a),$^{4)}$ and it is called CCTSH (Continuous Cooling Transformation Structure Hardness) curve hereafter. In the figure τ_{M100} and τ_{M0} indicate the critical cooling time at which quantity of martensite becomes 100 and 0%, respectively. The solid line in (b) shows the actual hardness curve (CCTSH curve) which enables us to suggest the hardness of HAZ in various welding conditions using any kind of heat source. It is clear from Fig. 2 (b) the hardness is closely connected with the quantity of martensite in the structure. For example in the region of short cooling time (small τ) with 100% martensite it keeps almost a constant value. While in a long time duration (large τ) it decreases sharply in relation to the martensite.

The solid line in **Fig. 3** shows the approximated H_v-τ curve corresponding to the proposed hardness equation in this research. A and B in the figure are the critical points showing 100% and 0% martensite, respectively. $H_v(\tau_{M100})$ means the hardness at τ_{M100}. C corresponds to the critical ferrite separation point.

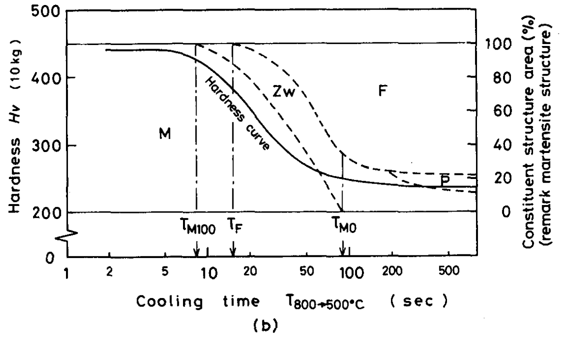
The following assumptions are made in obtaining the appropriate hardness curve.

(i) the hardness saturates at $\tau<\tau_{M100}$ with a value $H_v(\tau_{M100})$.

(ii) In the region of $\tau>\tau_{M100}$ the hardness decreases exponentially passing through points B (or B and C) and shows an asymptote with $\tau\rightarrow\infty$. Knowing the characteristic values at the critical points A and B (or A, B and C) the necessary hardness curve could thus be obtained. Such $H_v-\tau$ curve is called the "characteristic hardness curve" which is approximate to the CCTSH curve (actual hardness curve). The hardness equation (characteristic hardness curve) estimated from such A and B-characteristic values is called as Empirical Formula α and the one from A, B and C-characteristic values as Empirical Formula β. (As for the practical form of the equations, refer to eqs. (16)~(18).)



(a): welding CCT (continuous cooling transformation) diagram



(b): welding CCTSH (continuous cooling transformation structure hardness) diagram

Fig. 2 Relation between welding CCT diagram and hardness curve

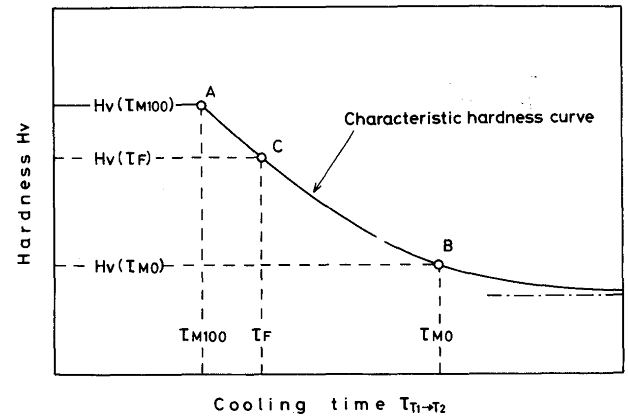


Fig. 3 Relation between A, B, C-characteristic each point, cooling time and hardness (This relation is called characteristic hardness curve which is compared with CCTSH actual curve)

3. Numerical Treatment of the Characteristic Values and the Empirical Formula

3.1 Numerical treatment of the characteristic values

Each characteristic value can be analyzed regressively and in the regression it is assumed that the value depends only on the alloy-elements and each element is a linear independent operator for every characteristic values. A lot of welding CCT diagrams which were obtained by Inagaki et al.$^{3\text{-}11)}$ for about 70 kinds of steels in **Table 1** were adopted for such treatment. In the practical analysis the materials are classified into the conventional welding steels (Si-Mn type steels) and the HT-steels. For the former materials the alloy-elements except C, Si, Mn are included only below 0.1%.

Table 1 Chemical composition range of CCT diagram used.

Chemical Composition	Range (%)
C	0.07 ~ 0.53
Mn	0 ~ 1.50
Si	0 ~ 0.60
Ni	0 ~ 3.50
Cr	0 ~ 1.50
Mo	0 ~ 0.60
V	0 ~ 0.15
B	0 ~ 0.01

a) Each characteristic value for the conventional welding steels.

A-characteristic value: (it is defined as the one at the critical point A)

$$H_v(\tau_{M100}) = 835[C] + 287\,, \qquad \cdots\cdots (4)$$

$$\log \tau_{M100} = 2.55([C] + \frac{1}{6.3}[Mn] + \frac{1}{3.6}[Si]) - 0.92\,. \qquad \cdots\cdots (5)$$

B-characteristic value: (defined at B)

$$H_v(\tau_{M0}) = 273([C] + \frac{1}{13}[Mn] + \frac{1}{9.7}[Si]) + 133\,, \qquad \cdots\cdots (6)$$

$$\log \tau_{M0} = -0.37([C] - \frac{1}{1.1}[Mn] - \frac{1}{0.44}[Si]) + 1.02\,. \qquad \cdots\cdots (7)$$

C-characteristic value: (defined at C)

$$H_v(\tau_F) = -277([C] - \frac{1}{12}[Mn] - \frac{1}{2.4}[Si]) + 339\,, \qquad \cdots\cdots (8)$$

$$\log \tau_F = 5.77([C] + \frac{1}{17}[Mn] + + \frac{1}{14}[Si]) - 0.88\,. \qquad \cdots\cdots (9)$$

b) The characteristic value for HT-steels.

A-characteristic value:

$$H_v(\tau_{M100}) = 835[C] + 287\,, \qquad \cdots\cdots (10)$$

$$\log \tau_{M100} = 5.9([C] + \frac{1}{19}[Mn] + \frac{1}{14}[Si] + \frac{1}{37}[Ni] + \frac{1}{19}[Cr] + \frac{1}{9.1}[Mo] - \frac{1}{49}[V] + \frac{1}{0.31}[B]) - 1.13\,. \qquad \cdots\cdots\cdot (11)$$

B-characteristic value:

$$H_v(\tau_{M0}) = 500([C] - \frac{1}{38}[Mn] - \frac{1}{68}[Si]$$

$$-\frac{1}{45}[Ni]+\frac{1}{9.0}[Cr]+\frac{1}{9.9}[Mo]$$

$$+\frac{1}{2.1}[V]+\frac{1}{0.48}[B])+153 \quad \ldots \quad (12)$$

$$\log \tau_{M0}=-0.20\,([C]-\frac{1}{4.3}[Mn]-\frac{1}{0.40}[Si]$$

$$-\frac{1}{0.58}[Ni]+\frac{1}{0.45}[Cr]-\frac{1}{0.49}[Mo]$$

$$+\frac{1}{240}[V]-\frac{1}{0.0024}[B])+1.60 \,.\,.\, (13)$$

C-characteristic value:

$$H_v(\tau_F)=288([C]+\frac{1}{4.6}[Mn]-\frac{1}{57}[Si]$$

$$+\frac{1}{33}[Ni]+\frac{1}{190}[Cr]-\frac{1}{68}[Mo]$$

$$-\frac{1}{2.0}[V]-\frac{1}{0.43}[B])+294\,, \quad .\,.\, (14)$$

$$\log \tau_F=6.18([C]+\frac{1}{17}[Mn]+\frac{1}{35}[Si]$$

$$+\frac{1}{46}[Ni]+\frac{1}{15}[Cr]+\frac{1}{7.0}[Mo]$$

$$+\frac{1}{95}[V]+\frac{1}{0.14}[B])-0.93\,. \quad \ldots \quad (15)$$

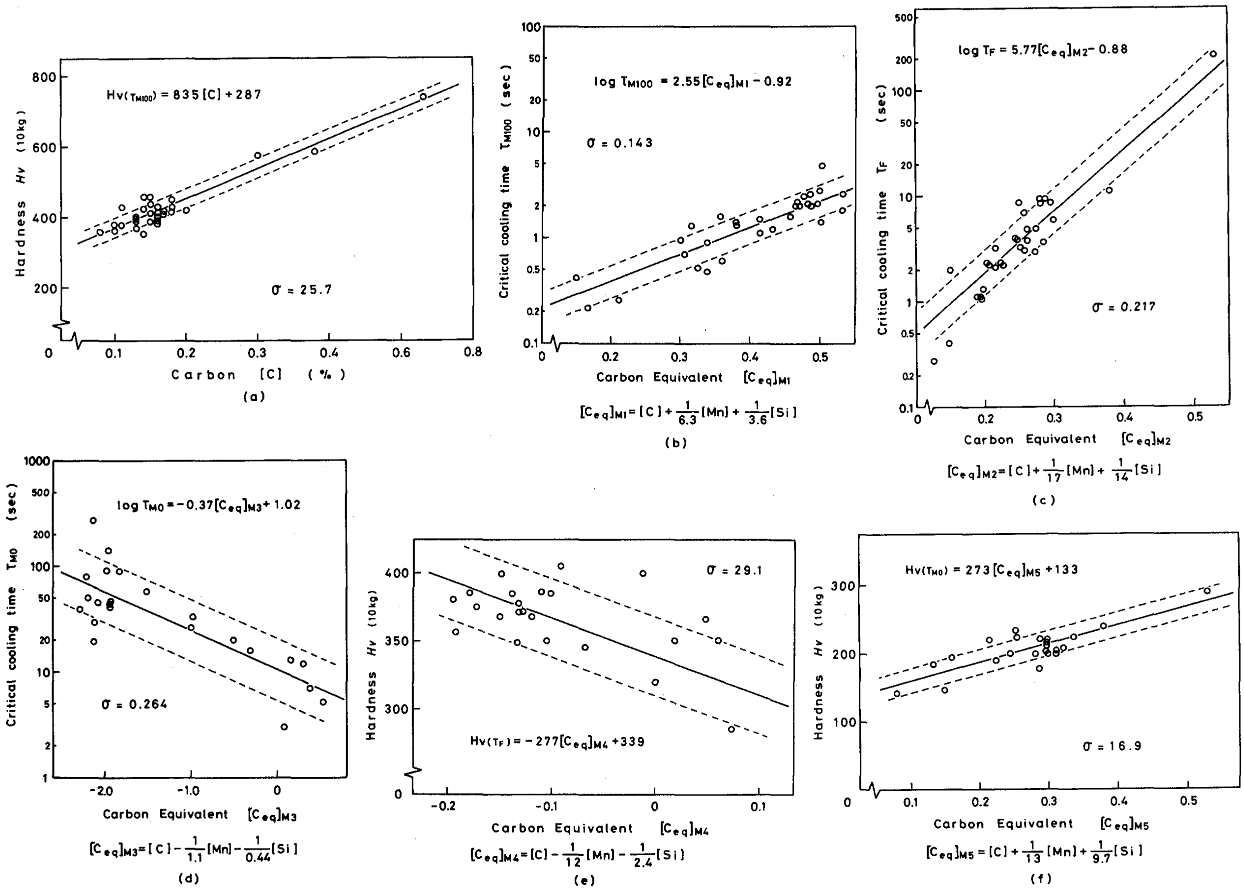
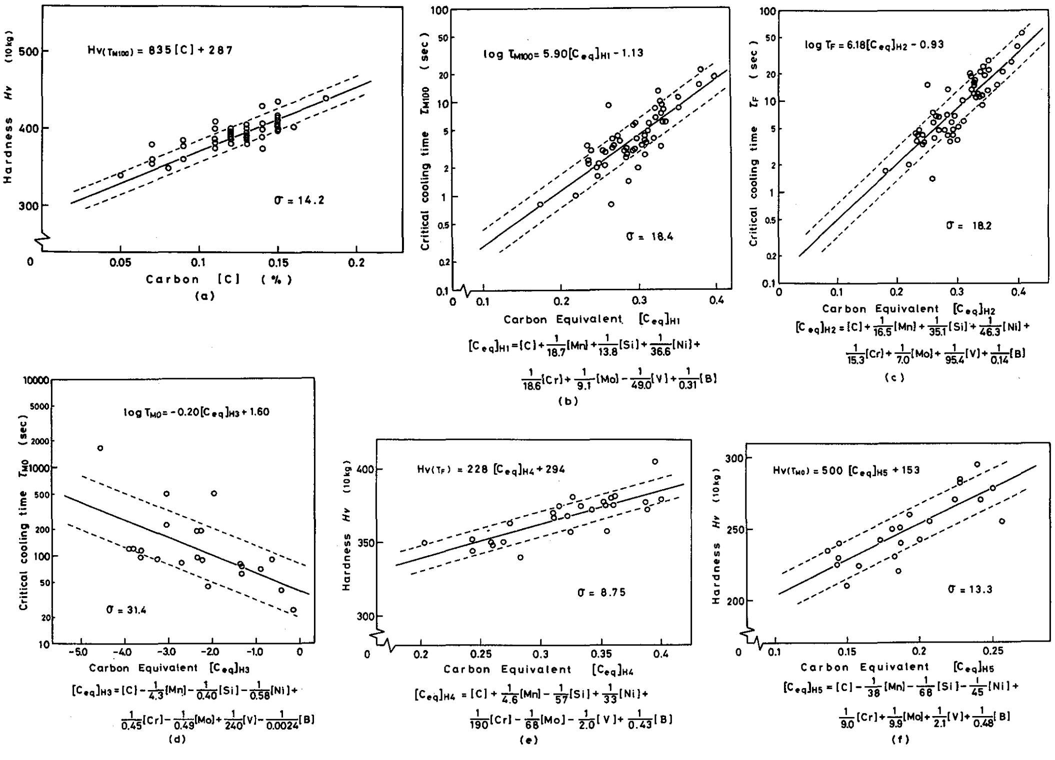


Fig. 4 Characteristic values for conventiond welding steels (Si-Mn type steel)

In the above equations $H_v(\tau_{M100})$ can be treated from the regression equation including only the term of carbon content, because 100% martensite structure hardness depends only on carbon content.[11]

Figure 4(a)~(f) and **Fig.** 5(a)~(f) show the results of eqs. (4)~(15). σ-values in the figures are the standard deviations obtained by using each regression equation. The solid line shows the regression equation and the dotted one corresponds to σ-value. For example in Fig. 4(a), σ-value of $H_v(\tau_{M100})$ in eq. (4) is estimated to be about ± 26 using 10Kg-Vickers hardness. $[C_{eq}]_{M1}$~$[C_{eq}]_{M5}$ are for some characteristic values of Si-Mn type steels. Indeed not all characteristic values are treated quite well as shown in the figures, but we can satisfactorily draw the hardness curve for any kind of steels using above equations.



$$[C_{eq}]_{H1}=[C]+\frac{1}{18.7}[Mn]+\frac{1}{13.8}[Si]+\frac{1}{36.6}[Ni]+\frac{1}{18.6}[Cr]+\frac{1}{9.1}[Mo]-\frac{1}{49.0}[V]+\frac{1}{0.31}[B]$$

(b)

$$[C_{eq}]_{H2}=[C]+\frac{1}{16.5}[Mn]+\frac{1}{35.1}[Si]+\frac{1}{46.3}[Ni]+\frac{1}{15.3}[Cr]+\frac{1}{7.0}[Mo]+\frac{1}{95.4}[V]+\frac{1}{0.14}[B]$$

(c)

$$[C_{eq}]_{H3}=[C]-\frac{1}{4.3}[Mn]-\frac{1}{0.40}[Si]-\frac{1}{0.58}[Ni]+\frac{1}{0.45}[Cr]-\frac{1}{0.49}[Mo]+\frac{1}{240}[V]-\frac{1}{0.0024}[B]$$

(d)

$$[C_{eq}]_{H4}=[C]+\frac{1}{4.6}[Mn]-\frac{1}{57}[Si]+\frac{1}{33}[Ni]+\frac{1}{190}[Cr]-\frac{1}{68}[Mo]-\frac{1}{2.0}[V]+\frac{1}{0.43}[B]$$

(e)

$$[C_{eq}]_{H5}=[C]-\frac{1}{38}[Mn]-\frac{1}{68}[Si]-\frac{1}{45}[Ni]+\frac{1}{9.0}[Cr]+\frac{1}{9.9}[Mo]+\frac{1}{2.1}[V]+\frac{1}{0.48}[B]$$

(f)

Fig. 5 Characteristic values for HT-steels

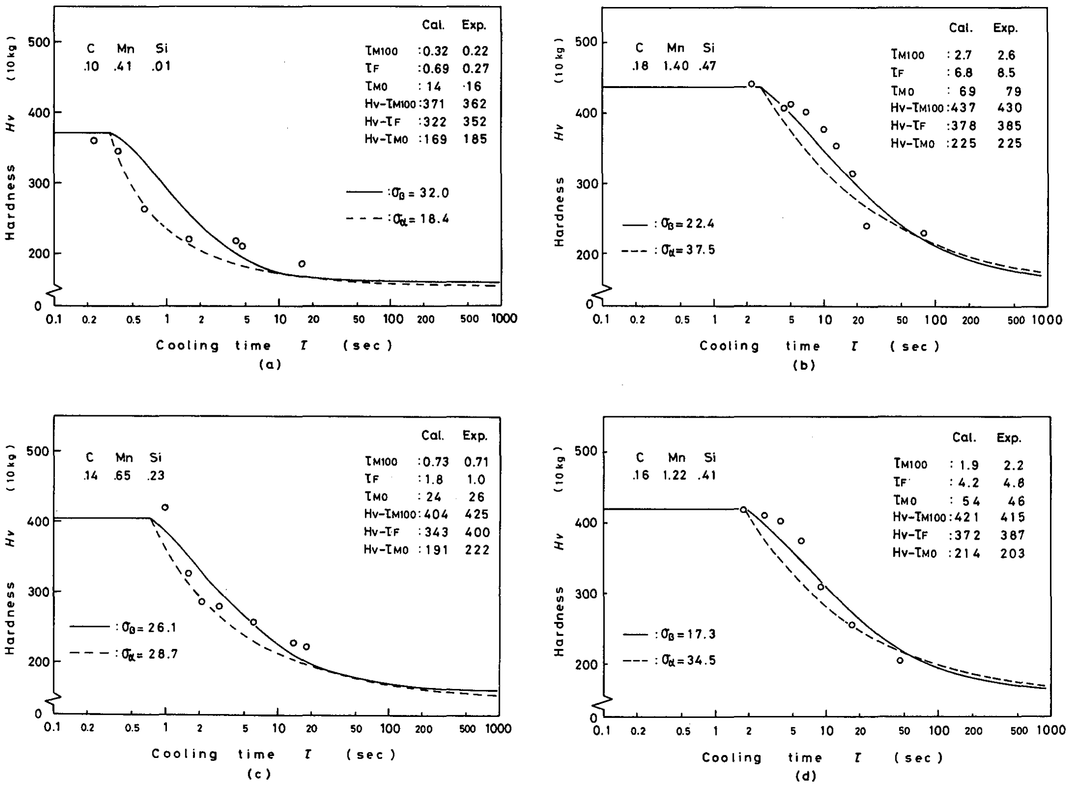


Fig. 6 Comparison between formula *α* (dashed line), formula *β* (solid line) and actual hardness (CCTSH; circles), using conventional welding steels

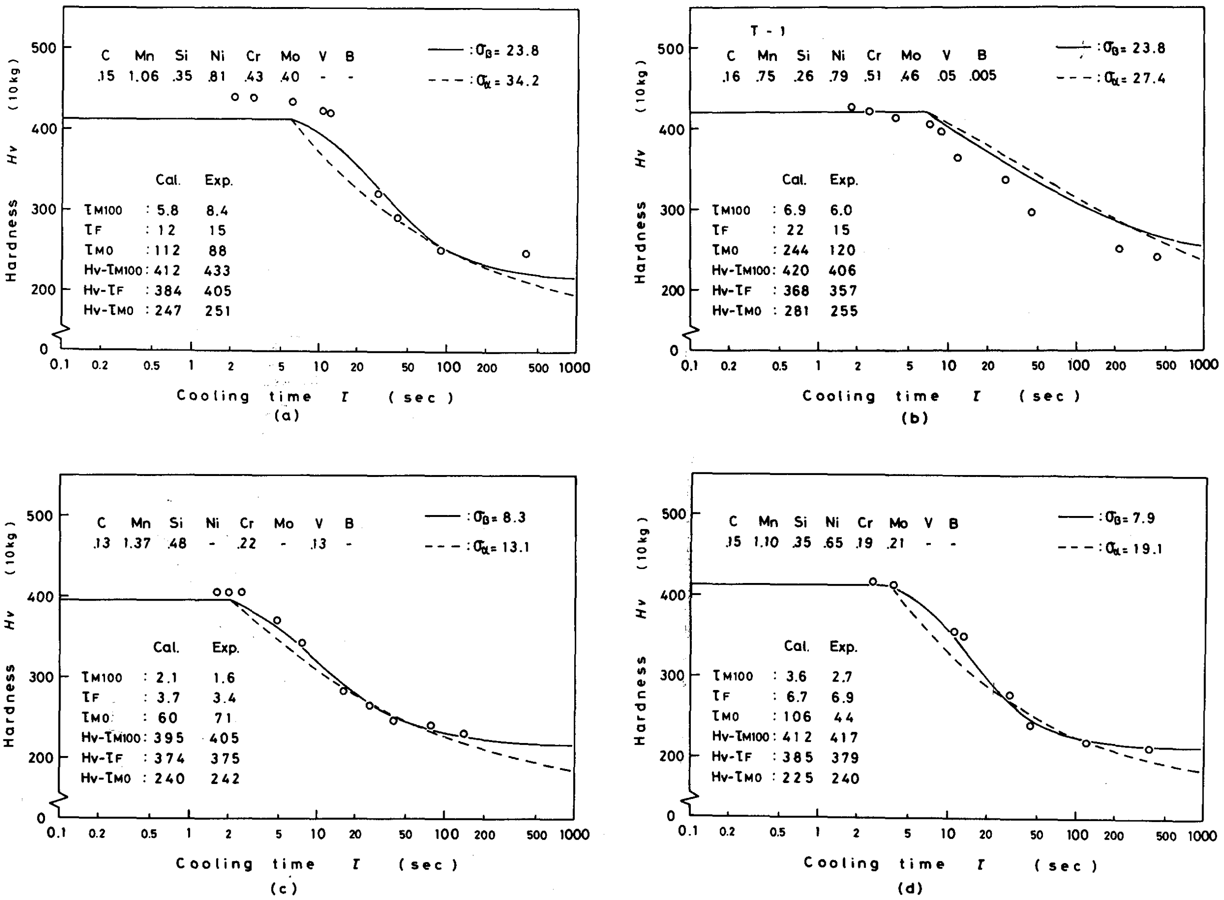


Fig. 7 Same examples as Fig. 6 using HT-steels

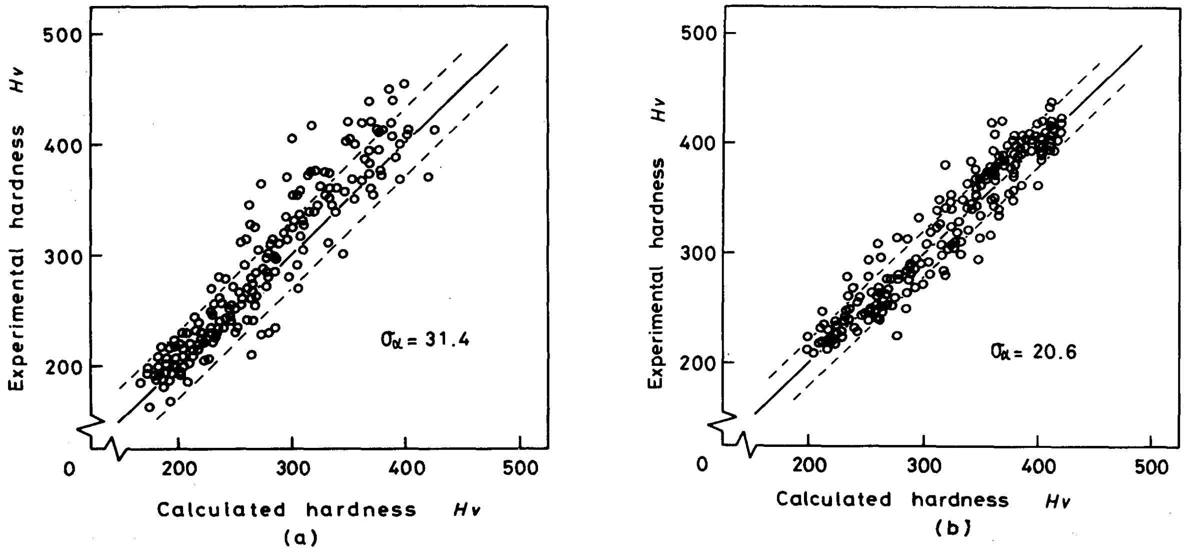


Fig. 8 Summarized result on usability of formula a
(a): Conventional steel (Si-Mn type)
(b): High strength steel

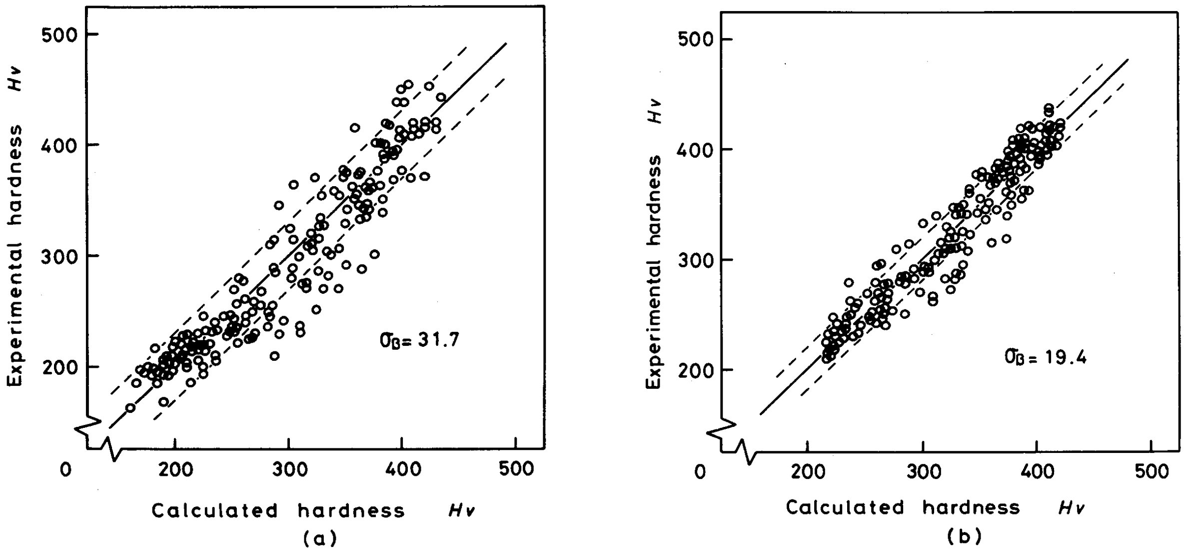


Fig. 9 Summarized result on usability of formula β
(a): Conventional steel (Si-Mn type)
(b): High strength steel

3.2 Empirical formula of the maximum hardness

In this section the characteristic hardness curves as shown in Fig. 3 are obtained by using eqs. (4)~(15) and compared with the actual ones.
The adopted formulas are as follows:
Empirical formula α

$$\tau > \tau_{M100}: \ H_v = \frac{b}{e^{\log \tau + a}} + 150\,(160), \quad .. \ (16)$$

$$\tau \leq \tau_{M100}: \ H_v = 835[C] + 287 . \quad \ldots\ldots \ (17)$$

Numerical constant 150 (160 in HT steels) in eq. (16) shows an asymptotic one for $\tau \to \infty$. When a steel is given, critical points A and B are calculated by using its chemical compositions and the characteristic values are substituted into eq. (16). Thus a, b are decided and the empirical equation is obtained.
Empirical formula β

$$\tau > \tau_{M100}: \ H_v = \frac{1}{e^{c' \log \tau + a'}} + 160 \quad (217 \text{ in HT}) \quad \ldots\ldots \ (18)$$

The procedure for obtaining a', b', and c' is quite similar

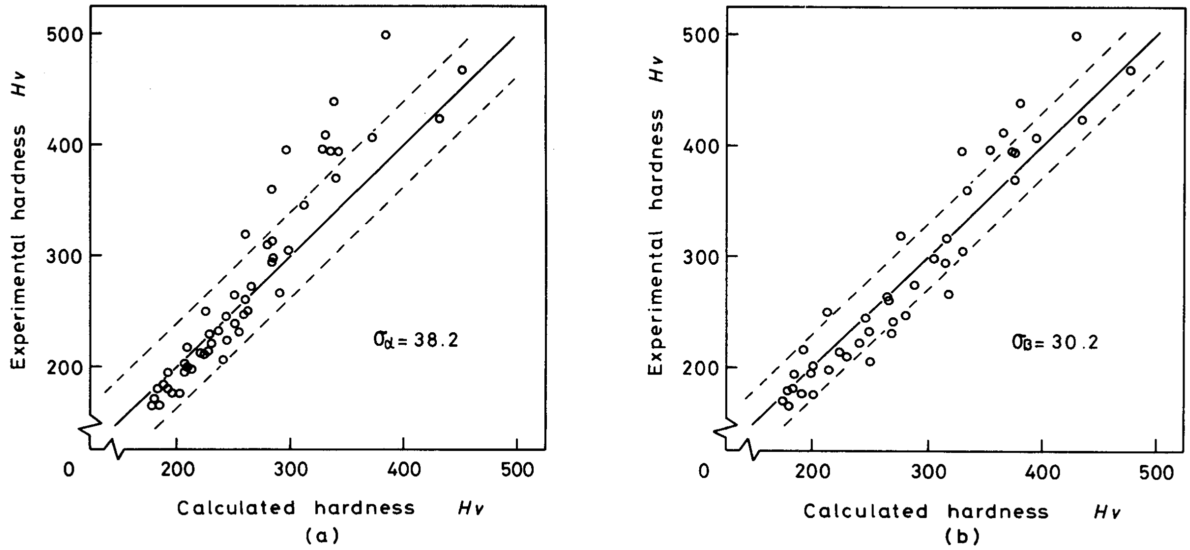


Fig. 10 Check of accuracy of formula α and β for conventional steels

to the case of eq. (16). For $\tau \leq \tau_{M100}$, eq. (17) is used.

Figure 6 and 7 show typical examples of comparison of the characteristic hardness obtained from the above method and the measured one by using welding CCT diagram (CCTSH). The standard deviations σ_α, σ_β are obtained by rearranging the measured hardness (circles in the figure) with the formulas α and β, respectively. Clearly the empirical formulas proposed in this paper satisfactorily reflect the actual hardness changes. In **Figs.** 8 and 9 are summarized calculated results by using both formulas. For any kind of steels the experimental and the calculated hardnesses agree quite well. We may say there is little difference between the formula α and β judging from values of the standard deviation.

4. Accuracy of Empirical Formulas

First of all the hardness of HAZ is discussed. All of the adopted specimens are heated at 1350°C in the maximum temperature. **Figure 10** shows the comparison of the calculated hardness with the measured ones by Yamamoto et al.[12] for 7 kinds of conventional welding steels. In the figure (a) corresponds to the formula α and (b) to β. There is a larger error in (a). **Figure 11** is the hardness curve for HT-steels obtained from the formula β. The experimental data shown for comparison were reproduced for 50 kinds of steels from welding CCT diagrams made at each steel maker (A~D Co.). Each analyzed result is

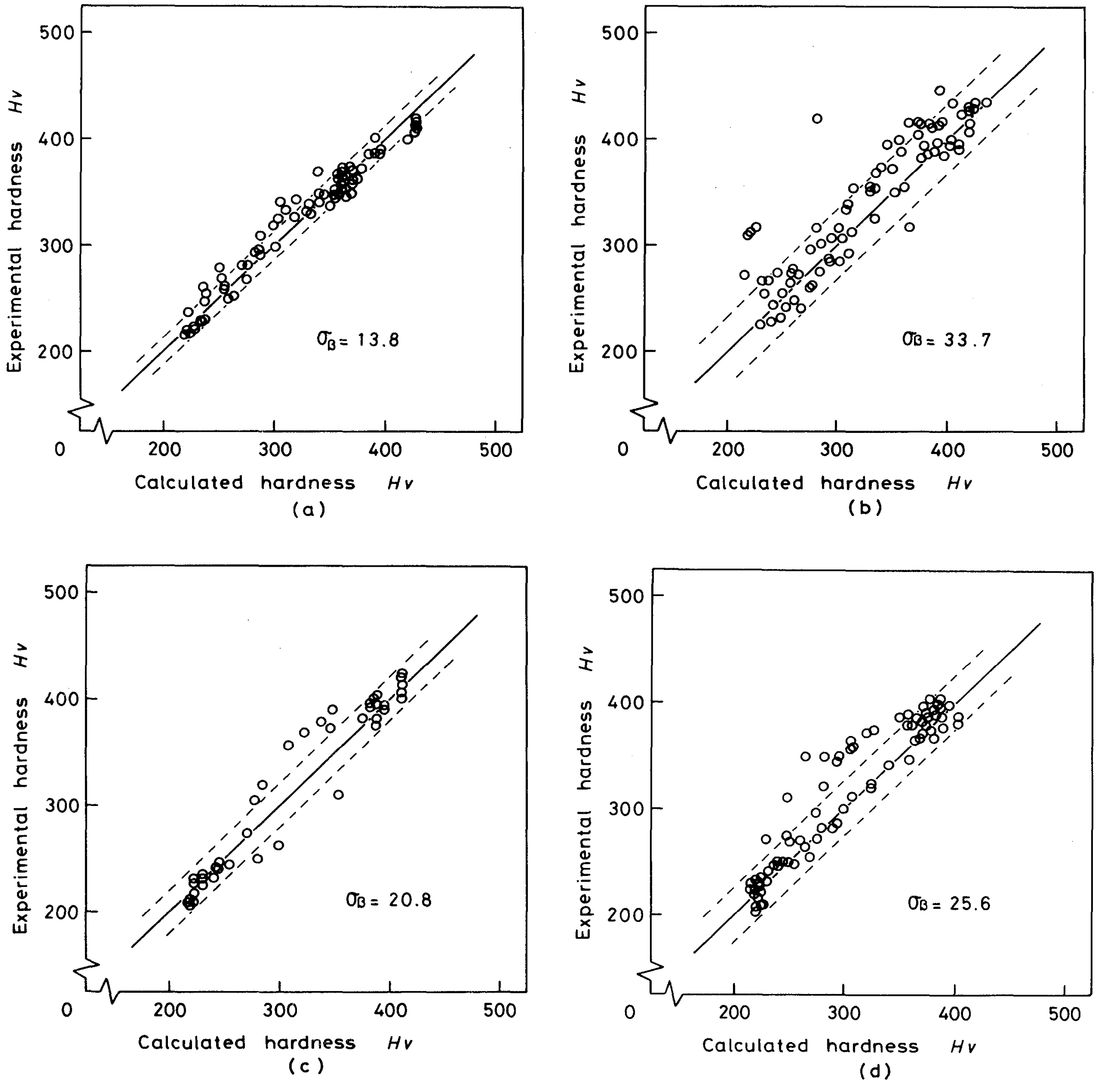


Fig. 11 Check of accuracy of formula β for 50 kinds of HT-steels

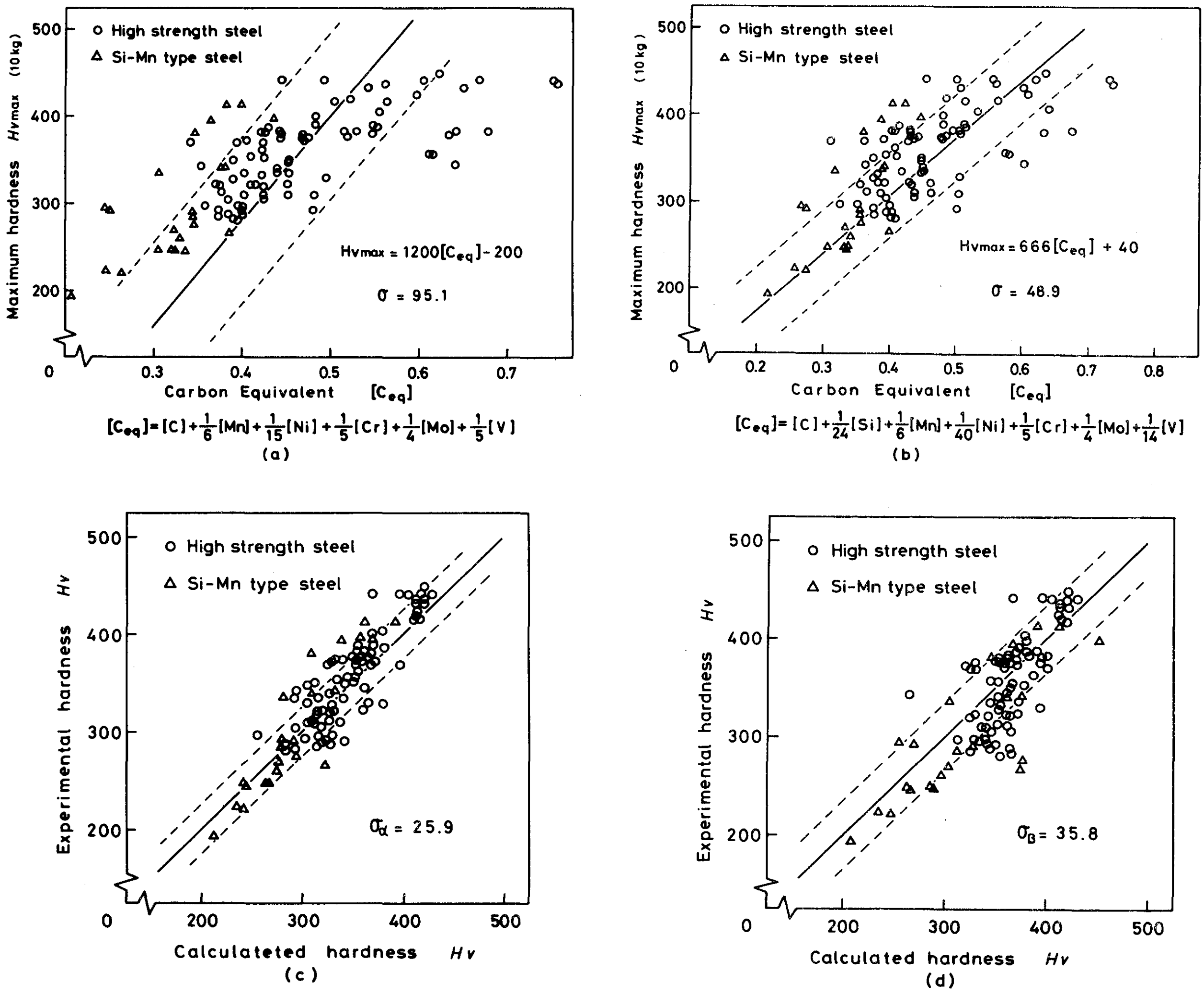
drawn with (a)~(d). In **Table** 2 the accuracy of the formula α and β for HT-steel are tabulated by the standard deviations σ_α and σ_β. (See also Fig. 8(b) and Fig. 9(b), σ-values in K of Table 2 were obtained from these figures.)

Table 2 Standard deviation using formula α and β for 50 kinds of HT-steels.

	K	A	B	C	D
σ_α	20.6	31.5	48.3	51.3	43.5
σ_β	19.4	13.8	33.7	20.8	25.6

From these results it can be concluded the hardness curve of CCT diagrams (CCTSH) can be estimated with a high accuracy by using the formula β.

Next, the actual hardness at HAZ are tested by Bessho's data.$^{13)}$ In his data of the maximum hardness, the welding conditions for 100 kinds of steels (Y-groove inner welding using *1mmφ* low hydrogen electrode) are as follows: welding current = 170A; arc voltage = 25; welding speed = 50mm/min. The measured cooling time τ is 4~6 sec. These conditions are typically used in the traditional method for estimating the hardness equation. The traditional method with only one parameter C_{eq} is compared with our result in which chemical composition and cooling time are included. **Figures** 12 (a) and (b) show the examples of the traditional hardness curve by Dearden et al.$^{14)}$ and Kihara et al.,$^{15)}$ respectively. They don't give a good result for estimation. While in Fig. 12(c) and (d) our results are shown, where the empirical formulas α and β give by far the more accurate results for wide welding conditions. Comparing (c) and (d) the formula α shows a better agreement than β in contrast to the case of Fig. 10 or Table 2, whose reasons are not



(a) (b) (c) (d)

Fig. 12 Comparison between traditional equations and formulas α, β under conventional arc welding condition clarified.

The result in **Fig. 13** is shown only for reference. The empirical formula (the solid line) gives a considerably good estimation to the experimental hardness$^{1)}$ of EB-welding part.

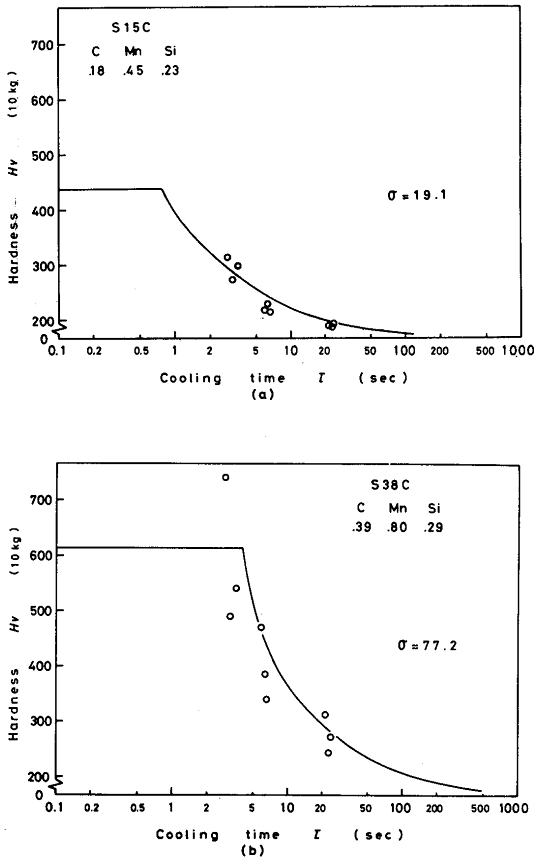


Fig. 13 Comparison between formula a (solid line) and experimental value (circle)

5. Conclusion

Data in CCT diagrams of steels were treated statistically and the estimation of the hardness in the weld part of many kinds of steels were performed. A new index in the evaluation of weldability of steels were obtained by this method.

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