Supplementary Technical Document for Senior Welding Engineer Certification

I. Determination of Necessary Preheat Temperature

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THE JAPAN WELDING ENGINEERING SOCIETY

1. Welding heat input

Heat supplied per unit weld length by a heat source is given as:

$$EI(J/cm) = 60 \cdot (I \cdot E / v) \quad (1)$$

or

$$EI(kJ/mm) = 0.006(I \cdot E / v) \quad (2)$$

where, I is welding current (A), E is welding voltage (V), and v is welding speed (cm/min). EI is called "energy input" in AWS (American Welding Society) and is same as AE (arc energy) used in EN (European Standard).

The energy supplied into a weld is HI (heat input):

$$HI(kJ/mm) = \eta \cdot EI \quad (3)$$

where, η is heat efficiency of a heat source.

η for SAW $\cong$ 1.0
η for SMAW $\cong$ 0.8
η for GMAW $\cong$ 0.8
η for TIG $\cong$ 0.6

2. HAZ hardness

The maximum HAZ hardness, $Hmax$ governs the occurrence of cold cracking and sulfide stress corrosion cracking. So, the limitation of $Hmax$ is often specified in welding fabrication in such that $Hmax$ should be less than 350Hv for avoiding cold cracking, or be less than 248Hv for avoiding sulfide stress corrosion cracking.

$Hmax$ is determined by the welding cooling rate and chemical composition of a steel. The cooling rate in welding is generally represented by the cooling rate at 540°C, R_{540}(°C/s) or the cooling time between 800 and 500°C, $t_{8/5}$(s). This is because the phase transformation on cooling in a mild steel starts at about 800°C and finishes at about 500°C, There is the following relationship between R_{540}(°C/s) and $t_{8/5}$(s) :

$$R_{540}(^{o}C/s) \cong 300^{o}C / t_{8/5}(s) \quad (4)$$

$t_{8/5}$(s) changes depending upon the welding heat input, plate thickness, preheat and inter-pass temperature and ambient temperature. In order to obtain $t_{8/5}$(s), nomographs1) and charts2) are prepared. However, this can be online-calculated very easily at the website of the Japan Welding Engineering Society. Its URL is:

http://www-it.jwes.or.jp/weld_simulator/index.jsp

Fig.1 shows how $Hmax$ changes as $t_{8/5}$ changes. As $t_{8/5}$ decreases (the cooling rate increases), HAZ hardness increases and the HAZ microstructure becomes hardened martensite. As $t_{8/5}$ increases (the cooling rate decreases), HAZ hardness gradually decreases and the volume of martensite in HAZ decreases. The HAZ microstructure consists of 100% martensite at the cooling times shorter than the point A, while it does of 0% martensite at the cooling times longer than the point B. The hardness of 100% martensite is determined solely by the carbon content. Haradenability of a steel represents how easily the martensite structure can be obtained in a heat-treated steel or steel HAZ. As hardenability increases, the Hmax- $t_{8/5}$ curve shifts to the right hand side; i.e., the martensite microstructure can be obtained even at the longer $t_{8/5}$(slower cooling rate).

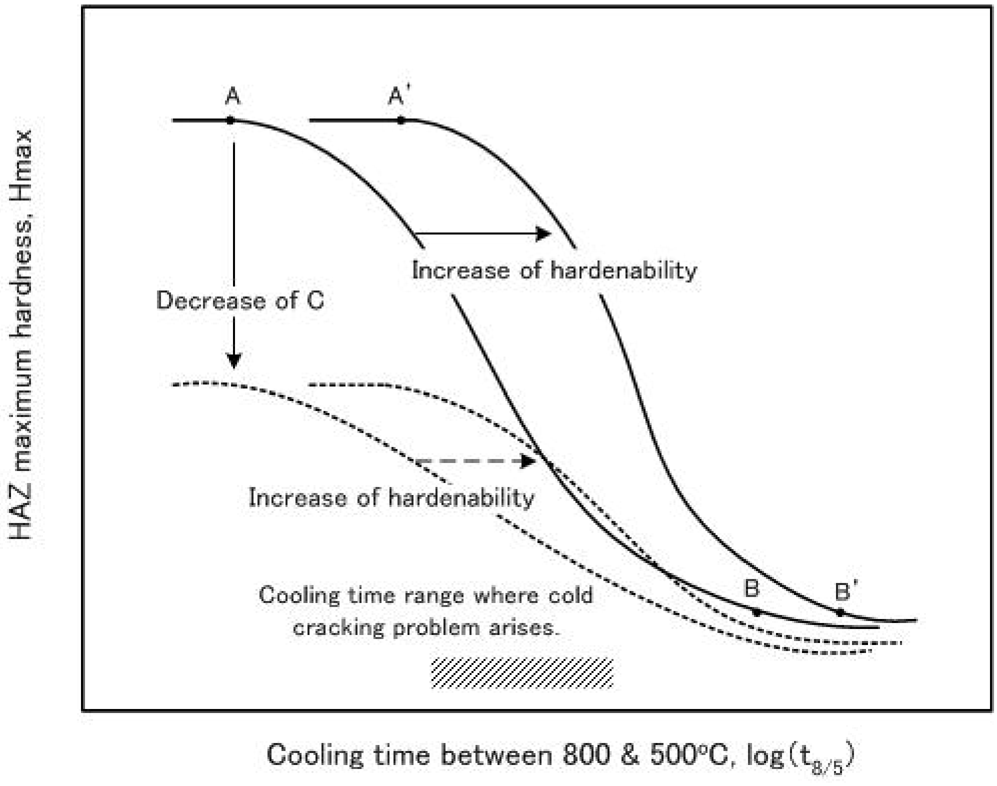


Fig.1 The effect of steel composition on Hmax- $t_{8/5}$ relation

Based on the principle of the hardness behavior above-mentioned, the following *Hmax* prediction formula is porposed[3):

$$H_{MAX} = \frac{H_M + H_B}{2} - \frac{H_M - H_B}{2.2}\arctan(x) \qquad (5)$$

$$x = 4\frac{log(t_{8/5} / t_M)}{log(t_B / t_M)} - 2$$

where, $t_{8/5}$ is given by the welding conditions (heat input, plate thickness, preheat temperature), and H_M, H_B, t_M, t_B are given by the steel chemical composition as follows:

H_M : 100% martensite hardness:

$$H_M = 884C(1-0.3C^2)+294 \tag{6}$$

t_M: the critical (longest) cooling time when HAZ becomes 100% martensite (point A):

$$t_M = exp(10.6CE_I - 4.8) \tag{7}$$

$$CE_I = C + \frac{Si}{24} + \frac{Mn}{6} + \frac{Cu}{15} + \frac{Ni}{12} + \frac{Mo}{4} + \frac{Cr(1-0.16\sqrt{Cr})}{8} \tag{8}$$

CE_I is the carbon equivalent representing HAZ hardenability and its applicable range is $C \leq 0.3\%$.

H_B : 0% martensite hardness:

$$H_B = 145 + 130\tanh(2.65CE_{II} + 0.74) \tag{9}$$

$$CE_{II} = C + \frac{Si}{24} + \frac{Mn}{5} + \frac{Cu}{10} + \frac{Ni}{18} + \frac{Cr}{5} + \frac{Mo}{2.5} + \frac{V}{5} + \frac{Nb}{3} \tag{10}$$

t_B : the critical (shortest) cooling time when HAZ becomes 0% martensite (point B):

$$t_B = exp(6.2CE_{III} + 0.74) \tag{11}$$

$$CE_{III} = C + \frac{Mn}{3.6} + \frac{Cu}{20} + \frac{Ni}{9} + \frac{Cr}{5} + \frac{Mo}{4} \tag{12}$$

The HAZ maximum hardness, *Hmax* given by the above equations can be online-calculated very easily at the website of the Japan Welding Engineering Society. Its URL is:

http://www-it.jwes.or.jp/weld_simulator/index.jsp

3. Carbon equivalent

Weldability of a steel represents, in a narrow sense, how HAZ hardens. HAZ hardness is directly related with susceptibility to hydrogen induced cold cracking. Therefore, good weldability means that HAZ is less hardened and thereby more resistant to the occurrence of cold cracking. As shown in Fig.1, HAZ hardness is determined by the carbon content and HAZ hardenability. Cold cracking becomes a problem generally when the heat input is between 0.8 and 2.0kJ/mm ($t_{8/5}$ is between 4 and 11s). In this condition, HAZ hardness significantly changes as hardenability changes for a steel containing rather high content of carbon. However, for a steel with lesser amount of carbon, HAZ hardness is less affected by hardenability. Rather, it is more influenced by the carbon content itself.

Table 1 shows well known carbon equivalents The carbon equivalent of group A is similar to Eq. 8. Therefore, this type of carbon equivalent represents HAZ hardenability and is considered to be an index of weldability of a steel containing rather high content of carbon. CE_{IIW} in this group is widely used and carbon equivalent often means CE_{IIW}. Pcm of group C, in which the effect of carbon is significant, is thereby considered to be an index of weldability of a steel with reduced carbon. CE_T of group B is in between group A and B$^{4)}$.

Table 1 Carbon equivalents mainly used

Group	Carbon equivalent formula	Applicable range	Specification
A	$CE_{IIW} = C + \frac{Mn}{6} + \frac{Cu+Ni}{15} + \frac{Cr+Mo+V}{5}$ $CE_{WES} = C + \frac{Si}{24} + \frac{Mn}{6} + \frac{Ni}{40} + \frac{Cr}{5} + \frac{Mo}{4} + \frac{V}{14}$	$C \geq 0.08\%$	AWS D1.1 BS 5135 EN 1011-2-2001 旧 WES 3001
B	$CE_T = C + \frac{Mn}{10} + \frac{Cu}{20} + \frac{Ni}{40} + \frac{Cr}{20} + \frac{Mo}{10}$	$0.08 \leq C \leq 0.12\%$	EN 1011-2-2001
C	$Pcm = C + \frac{Si}{30} + \frac{Mn}{20} + \frac{Cu}{20} + \frac{Ni}{60} + \frac{Cr}{20} + \frac{Mo}{15} + \frac{V}{10} + 5B$	$C \leq 0.12\%$	WES 3009 AWS D1.1
D	$CE_N = C + f(C) \cdot \left\{ \frac{Si}{24} + \frac{Mn}{6} + \frac{Cu}{15} + \frac{Ni}{20} + \frac{Cr+Mo+Nb+V}{5} \right\}$ $f(C) = 0.75 + 0.25 \cdot \tanh\{20(C - 0.12)\}$	$C \leq 0.3\%$	ASTM A 1005/A-00 ASME B16.49-2000

Table 2 Coefficient of CE_N carbon equivalent

C(%)	$f(C)$	C(%)	$f(C)$	C(%)	$f(C)$	C(%)	$f(C)$
0.02	0.51	0.08	0.58	0.14	0.85	0.20	0.98
0.03	0.51	0.09	0.62	0.15	0.88	0.21	0.99
0.04	0.52	0.10	0.66	0.16	0.92	0.22	0.99
0.05	0.53	0.11	0.70	0.17	0.94	0.23 以上	1.00
0.06	0.54	0.12	0.75	0.18	0.96		
0.07	0.56	0.13	0.80	0.19	0.97		

As shown by the change of HAZ hardness in Fig.1, HAZ hardness is determined by an interactive effect of the carbon content and HAZ hardenability. Therefore, there must be an applicable range depending on the carbon content for each carbon equivalent in the groups of A, B and C in Table 1. CE_N carbon equivalent of group D considers the interactive effect of C and hardenability5). It approaches to CE_{IIW} as C increases, while it approaches to *Pcm* as C decreases. It is considered to be an index of weldability of a wide range of steel.

4. Determination of Necessary minimum preheat temperature

1) Hardness control method of American Welding Society (AWS) D1.1, ANNEX I ($C \geq 0.11\%$)

This method avoids cold cracking by reducing HAZ hardness less than the critical level through reducing the cooling rate or increasing cooling time. As shown in Fig.1, the reduction of HAZ hardness by increasing $t_{8/5}$ is effective for a steel with a rather high content of C. The AWS D1.1, ANNEX I specifies that this method is applicable for a steel with carbon higher than 0.11%.

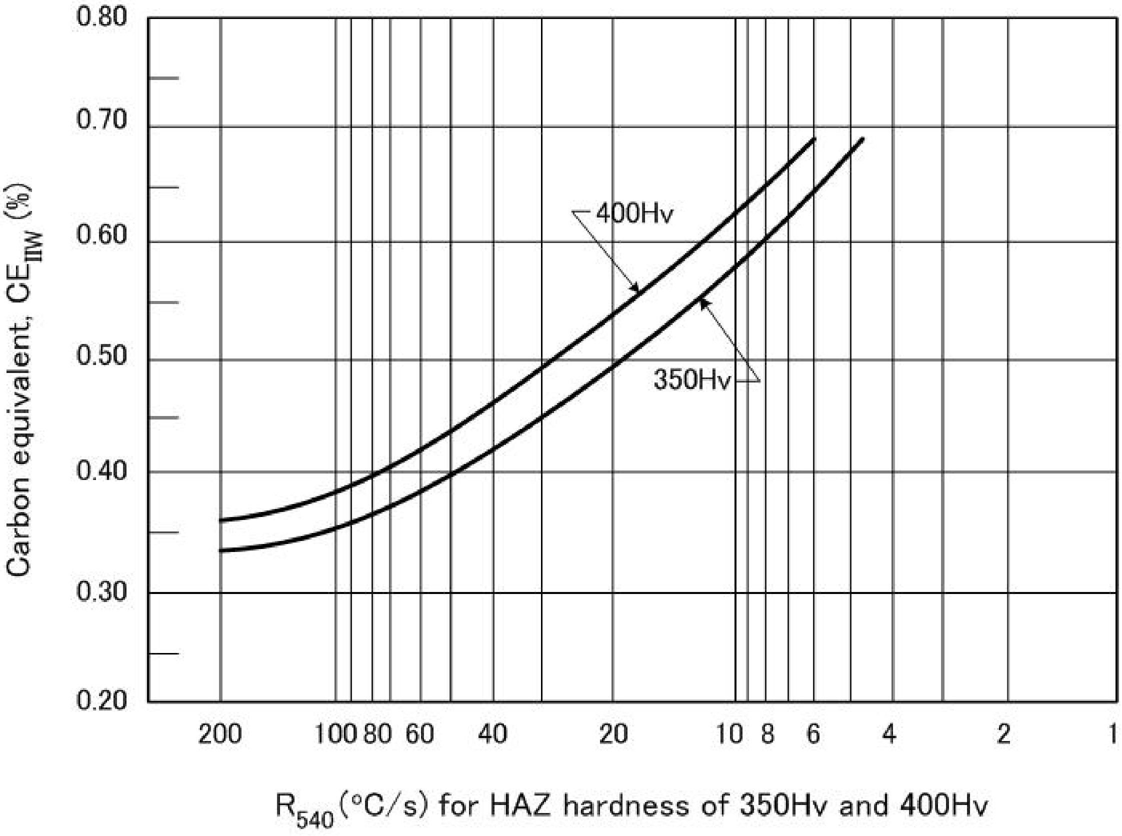


Fig. 2 Critical cooling rate to obtain critical HAZ hardness

Fig.2 shows the critical cooling rate, R_{540}(°C/s) necessary to satisfy the critical hardness of 350Hv and 400Hv for a given CE_{IIW}. For fillet welding, the cooling rate is governed by the web and flange thickness. AWS D1.1 prepared a number of figures which show the relation of R_{540}(°C/s) to the web and flange thickness, and the energy input. Fig. 3 is one example for the 12mm web thickness. The energy input (*EI*) to avoid cold cracking in this method is given, first by obtaining the critical R_{540}(°C/s) against the critical hardness (350Hv or 400Hv) in Fig. 2 and secondly by finding *EI* corresponding to the web and flange thicknesses and R_{540}(°C/s) in Fig.3.

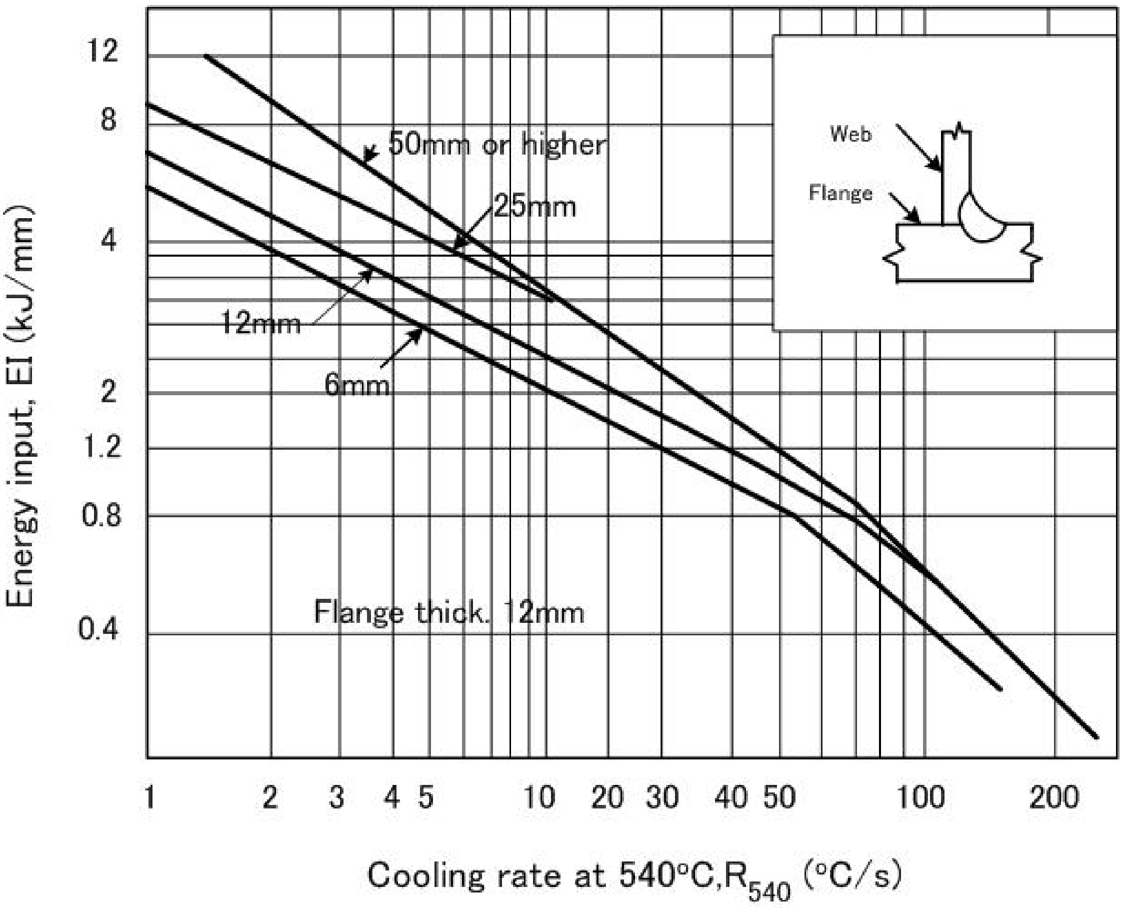


Fig.3 Minimum energy input for critical cooling rate (flange thickness of 12mm)

EI of the vertical axis of Fig.3 is for SAW. In the case of welding processes other than SAW, the minimum necessary energy input is given by multiplying the *EI* obtained for SAW (Fig.3) by the following factor..

Welding process	Multiplication factor
SAW	1.0
SMAW	1.50
GMAW, FCAW	1.25

2) Hydrogen control method of American Welding Society (AWS) D1.1, ANNEX I

($C < 0.11\%$)

This method avoids cold cracking by reducing diffusible hydrogen for a steel whose HAZ hardness changes little by decreasing R_{540} or increasing $t_{8/5}$. The AWS D1.1, ANNEX I specifies that this method is applicable for a carbon reduced steel ($C < 0.11\%$).

The susceptibility index, SI is given by:

$$SI = 12 \cdot Pcm + \log_{10} H_{GC} \qquad (13)$$

where, Pcm is carbon equivalent of group C in Table 1 and H_{GC} is weld metal diffusible hydrogen content by a gas chromatography (JIS Z3118, ISO 3690). The necessary minimum preheat temperature is given by Table 3 according to the SI value, degree of restraint and plate thickness.

It should be noted that if this method is applied to a steel with higher content of carbon, too conservative (high) preheat temperatures are given[6).

Table 3 Necessary minimum preheat temperature by hydrogen control method

Restraint Level	Thickness (mm)	Susceptibility index, SI=12Pcm + $\log_{10} H_{GC}$						
		3.0	3.1 – 3.5	3.6 – 4.0	4.1 – 4.5	4.6 – 5.0	5.1 – 5.5	5.6 – 7.0
Low	< 10	< 20	< 20	< 20	< 20	60	140	150
	10 - 20	< 20	< 20	20	60	100	140	150
	20 - 38	< 20	< 20	20	80	110	140	150
	38 - 75	20	20	40	95	120	140	150
	> 75	20	20	40	95	120	140	150
Medium	< 10	< 20	< 20	< 20	< 20	70	140	150
	10 - 20	< 20	< 20	20	80	115	145	160
	20 - 38	20	20	75	110	140	150	160
	38 - 75	20	80	110	130	150	150	160
	> 75	95	120	140	150	160	160	160
High	< 10	< 20	< 20	20	40	110	150	160
	10 - 20	< 20	20	65	105	140	160	160
	20 - 38	20	85	115	140	150	160	160
	38 - 75	115	130	150	150	160	160	160
	> 75	115	130	150	150	160	160	160

3) Preheat specification in Table 3.2 in AWS D1.1

AWS D1.1 alternatively gives the necessary minimum preheat temperature as shown in Table 4.

Table 4 Necessary minimum preheat temperature
(Extracted from AWS D1.1 Table 3.2)

Steel		Welding process	Thickness, t(mm)	Necessary Preheat (°C)
ASTM	Corresponded JIS			
A36 A53 Gr.B A131 Gr.A,B A139 Gr.B A381 Gr.Y35	SM400A,B,C	SMAW with electrode other than low hydrogen type	$3 \le t \le 19$ $19 \le t \le 38$ $38 \le t \le 63.5$ $63.5 \le t$	None 66 107 150
Same as above and TS500MPa class of steel	SM400A,B,C SM490A,B,C SM490YA,YB SM520B,C	SMAW with low hydrogen electrode SAW GMAW	$3 \le t \le 19$ $19 \le t \le 38$ $38 \le t \le 63.5$ $63.5 \le t$	None 10 66 107

The necessary minimum preheat temperatures for ASTM steels other than those mentioned in Table 4 should be referred to AWS D1.1 Table 3.2.

4) BS5135-1984 (EN 1011-2 -2001 A) method

This method is similar to the AWS hardness control method in which cold cracking is avoided by increasing $t_{8/5}$ to reduce HAZ hardness. Therefore, CE_{IIW} is used in this method. Fig.4 shows a figure giving the necessary preheat temperature against the thickness and arc energy for the combinations of carbon equivalent and weld metal hydrogen content; a) CE_{IIW} :0.38 and H_{GC} higher than 15ml/100g; b) CE_{IIW} :0.40 and H_{GC} between 10 and 15ml/100g; c) CE_{IIW} :0.41 and H_{GC} between 5 and 10ml/100g; d) CE_{IIW} :0.46 and H_{GC} less than 5ml/100g. This method prepares 13 figures like Fig.5. The necessary preheat temperature is determined by selecting the figure corresponding to the given combination of CE_{IIW} and H_{GC}(JIS Z3118, ISO 3690).

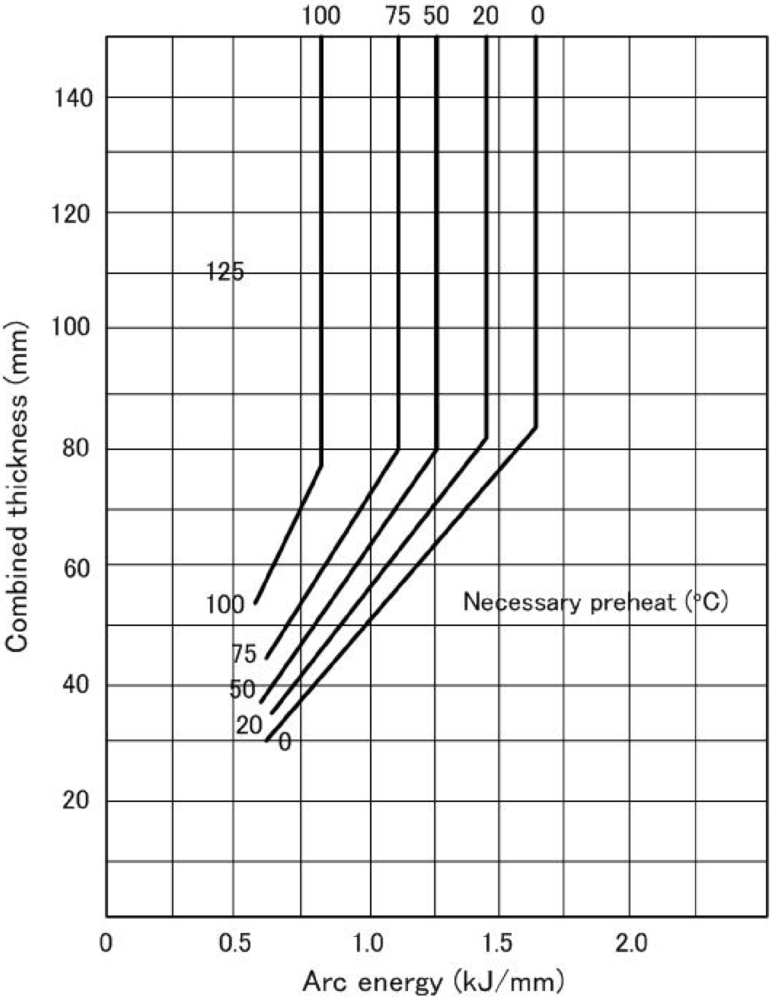
The arc energy, which is same as the energy input, in Fig. 4 is for SMAW. For the other processes with different heat efficiencies, the arc energy values calculated from Eq. (2) should be divided by the following factors to give the values to be used in Fig. 4.

SAW : 0.8

MAG (solid wire) : 1.0
MIG : 1.0
TIG : 1.2

The combined thickness, *CT* in Fig.4 is given as follows:

CT for butt joint = plate thickness x 2
CT for fillet joint = (flange thickness x 2 + web thickness)/2



H_{GC}	>15	10 – 15	5 – 10	<5
CE_{IIW}	0.38	0.40	0.41	0.46

Fig. 4 Necessary preheat temperature based on BS5135

5) Pc method (WES 3009)

The crack susceptibility index, *Pc* is given by *Pcm*, the weld metal diffusible hydrogen content, H_{GL} (ml/100g) and plate thickness, d(mm) as follows:

$$Pc = Pcm + \frac{H_{GL}}{60} + \frac{d}{600} \qquad (14)$$

where, Pcm is a carbon equivalent of C group shown in Table 1, H_{GL} is the weld metal diffusible hydrogen measured by the glycerin method (JIS Z3113). The glycerin method is poor in measuring accuracy and JIS Z3113 was abolished.

The minimum preheat temperature necessary for preventing root cracking in y-groove restraint cold cracking testing with the energy input of 1.7kJ/mm is given as follows:

$$T_{ph}\,(^{o}\mathrm{C}) = 1440\,Pc - 396 \qquad (15)$$

The y-groove restraint testing is conducted under a very sever condition of the high restraint, short bead, sever root notch and single pass. Therefore, the preheat temperature 75°C lower than that given by the y-groove restraint testing is generally adopted in welding of a TS490MPa grade of high strength steel. For steels with rather high carbon contents, this method gives too conservative (high) preheat temperature in the same way as the AWS hydrogen control method dose[6)].

6) Method by $\mathrm{CE_T}$[4)] (EN 1011-2-2001-B)

The minimum necessary preheat temperature is given by the following equation:

$$Tph(^{o}C) = 700CE_T + 160 \cdot \tanh(d/35) + 62H_{GC}^{0.35} - (32 - 53CE_T)HI - 330 \qquad (16)$$

where, CE_T is a carbon equivalent of the group B in Table 1, d(mm) is the plate thickness, H_{GC}(ml/100g) is the weld metal hydrogen content (JIS Z3118, ISO 3690), and HI(kJ/mm) is the heat input calculated by Eq.3.

This method gives appropriate preheat temperatures for steels with carbon contents between 0.08 and 0.12% but does too conservative preheat temperatures for both the rather high carbon steels and reduced carbon steels[6)].

7) Method by $\mathrm{CE_N}$[3)]

This method is based on the muster curves of the minimum preheat temperatures for y-groove restraint testing as a function of the group D of carbon equivalent, CE_N and the plate thickness (mm) shown in Fig.5. These master curves are for the standard condition of 5ml/100g of weld metal diffusible hydrogen content, H_{GC} (JIS Z3118, ISO 3690) and of 1.7kJ/mm of energy input, EI. Fig.6 shows the values of CE_N to be corrected by the deviation of H_{GC} from the standard, $\Delta\ CE_N(H_{GC})$, and Fig.7 shows the values of CE_N to be corrected by the deviation of EI from the standard, $\Delta\ CE_N(EI)$.

The energy input in Fig.7 is for SMAW (η=0.8). For the other process with a different heat efficiency, η, the arc energy values calculated from Eq. (2) should be multiplied by the following factors to give the values to be used in Fig. 7.

Welding process	Multiplying factor
SAW (η=1.0)	1.25
MAG (η=0.8)	1.0
MIG (η=0.8)	1.0
TIG (η=0.6)	0.75

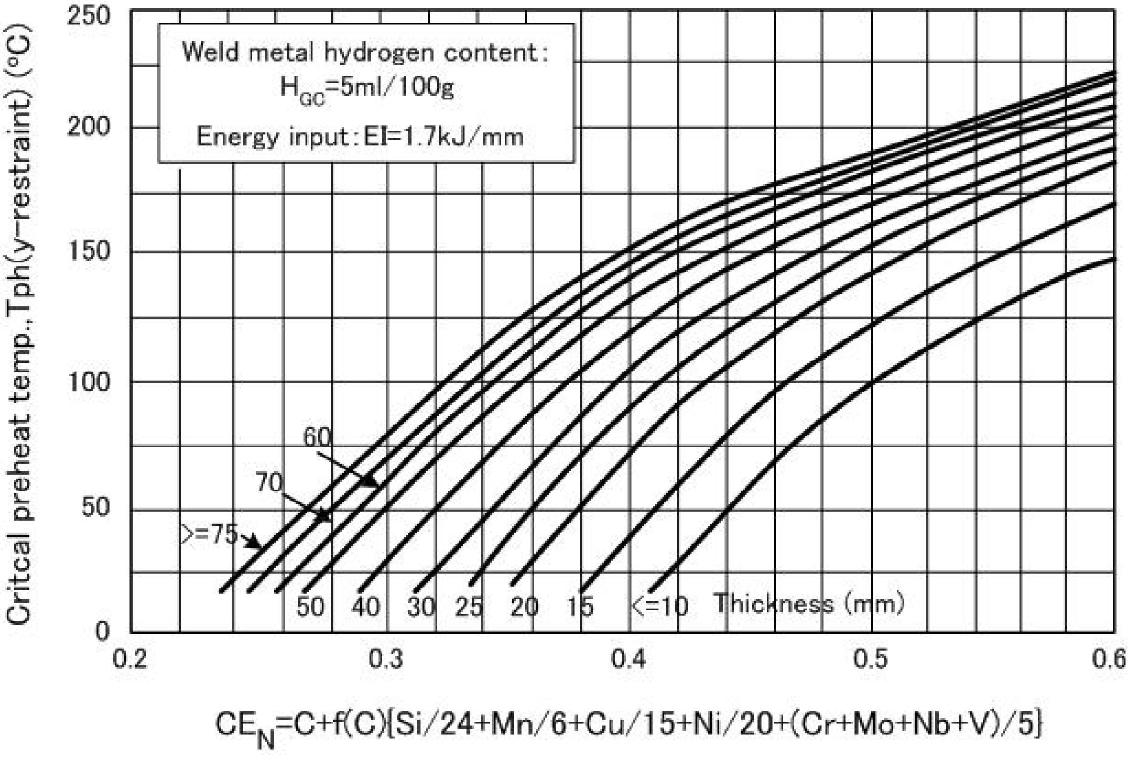


Fig. 5 Muster curves for necessary preheat by CE_N method

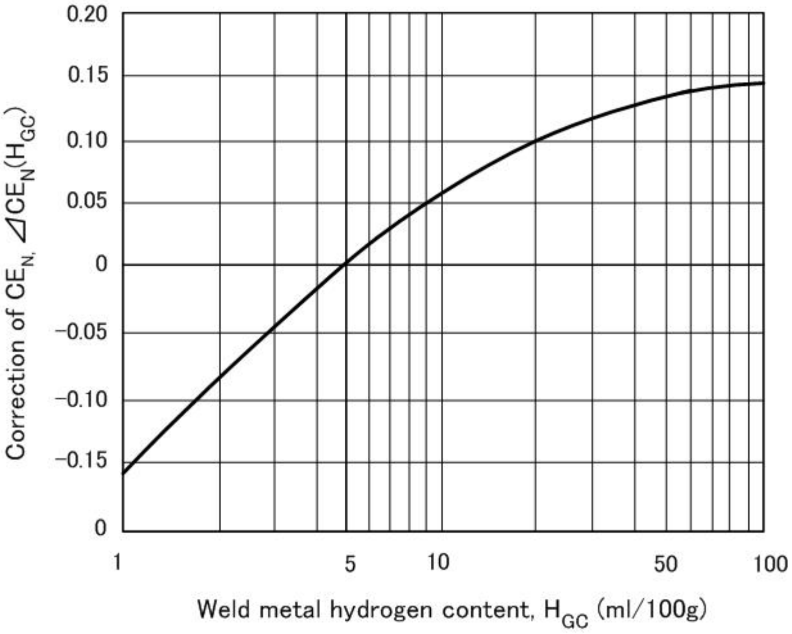


Fig. 6 Correction of CE_N according to H_{GC} deviation

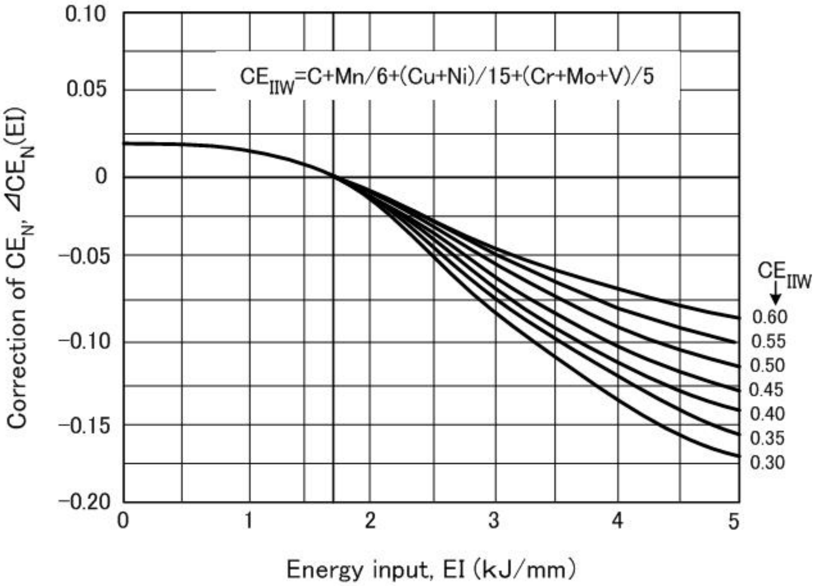


Fig. 7 Correction of CE_N according to EI deviation

CE_N corrected by the deviation of H_{GC} and EI from the standard is given as:

$$CE_N(\text{corrected}) = CE_N + \Delta CE_N\ (H_{GC}) + \Delta CE_N\ (EI) \qquad (17)$$

where, CE_N is the carbon equivalent value calculated from the steel composition. By introducing CE_N(corrected) into the horizontal axis of the master curves of Fig. 5, the necessary preheat temperature for y-groove testing, T_{ph}(y-restraint) is given.

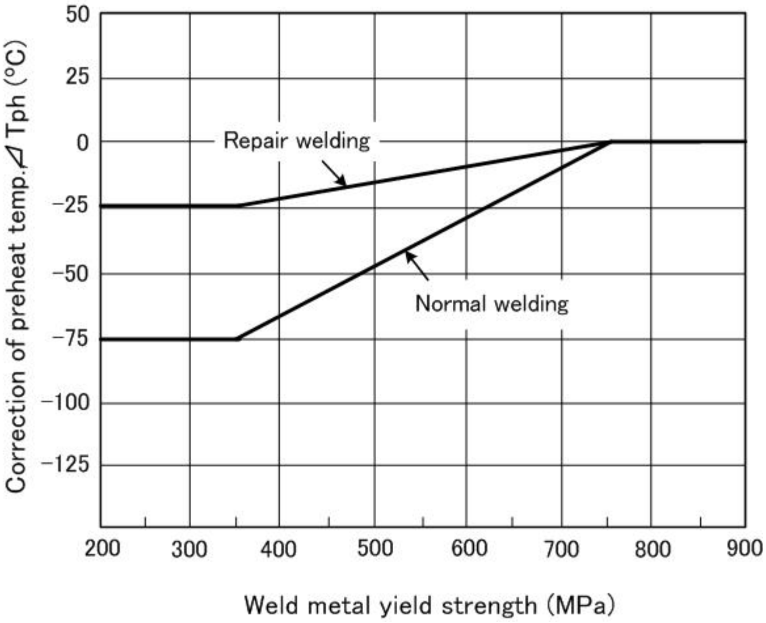


Fig. 8 Correction of necessary preheat according to weld metal yield strength

As mentioned above, T_{ph}(y-restraint) is not necessarily adopted as the preheat temperature in actual welding practices. Fig. 8 shows the values of the necessary preheat temperature to be corrected in welding practices, ΔT_{ph} (°C) from T_{ph}(y-restraint) depending on the weld metal yield strength. Finally, the necessary minimum preheat temperature in actual welding practices, T_{ph} (°C) is given as follows:

$$T_{ph}\ (^{o}\mathrm{C}) = T_{ph}(\text{y-restraint}) + \Delta T_{ph} \qquad (18)$$

The concept of the correction of the necessary preheat temperature of Fig. 8 is based on the following welding practice experiences: 1) the necessary preheating temperature can be reduced by 75°C from T_{ph}(y-restraint) in TS490MPa or YS360MPa steels; 2) cold cracking such as toe cracking, under-bead cracking, and weld metal cracking is more likely to occur as the welding residual stresses increase, i.e., the weld metal yield strength increases.

This method uses many figures and thus, a calculation error may arise. It is recommended to use online calculation provided by the Japan Welding Engineering Society whose URL is http://www-it.jwes.or.jp/weld_simulator/index.jsp.

8) Specification by the Japan Road Association

According to the Specification of Highway Bridges, the Japan Road Association, the necessary preheat temperature is given as shown in Table 5:

9) Specification by the High Pressure Institute of Japan

According to the standard of the use of high strength steels, the High Pressure Institute of Japan, the necessary minimum preheat temperature is given as shown in Table 6:

10) Preheat temperature standard for heat resistant steels

The necessary preheat temperature ranges for heat resistant steels are given as shown in Table 7[7):

Table 5 Standard condition for necessary preheat temperature

Steel	Welding process	Preheat temperature (°C)			
		Plate thickness (mm)			
		25 or less	40 or less	50 or less	100 or less
SM400	SMAW with electrode other than low hydrogen type	None	50	-	-
	SMAW with electrode of low hydrogen type	None	None	50	50
	SAW GMAW	None	None	None	None
SMA400W	SMAW with electrode of low hydrogen type	None	None	50	50
	SAW GMAW	None	None	None	None
SM490 SM490Y	SMAW with electrode of low hydrogen type	None	50	50	80
	SAW GMAW	None	None	50	50
SM520 SM570	SMAW with electrode of low hydrogen type	None	80	80	100
	SAW GMAW	None	50	50	80
SMA490W SMA570W	SMAW with electrode of low hydrogen type	None	80	80	100

	SAW GMAW	None	50	50	80

Table 6　Necessary minimum preheat temperature for high strength steels

Thickness t (mm)	Necessary minimum preheat (°C)	
	TS590MPa class	TS780MPa class
$t \le 19$	none	100
$19 < t \le 25$	60	125
$12 < t \le 32$	75	150
$32 < t \le 38$	100	
$38 < t \le 50$	125	
$50 < t \le 76$		−

Table 7　Necessary preheat temperature range for heat resistant steels

Steel	0.5Mo 0.5Cr−0.5Mo 0.75Cr−0.5Mo	1Cr−0.5Mo 1.25Cr−0.5Mo	2.25Cr−1Mo 3Cr−1Mo	5Cr−0.5Mo 9Cr−1Mo	Enh.2.25CR−1Mo 2.25Cr−1Mo−V 3Cr−1Mo−V
P−number	3−1, 3−2	4−1	5−1	5−2	5C−1
Preheat temp., (°C)	80 - 200	120−300	150−350	200−350	200−350

References

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