HARDNESS FUNCTIONS TO PREDICT WELDABILITY OF LOW CARBON STEEL
(Data to Computer Data Bank)

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1. Abstract

The determination of the expectable hardness of a welded joint can be carried out in the knowledge of the cooling time from 850 °C to 500 °C with function $HV-\Delta t_{8/5}$ characteristic of the given material. On the basis of the known hardness criterion it can be determined whether the technology causing the given cooling time can be used or not.

Direct connection is tried to be found between hardness and cooling time starting from relations in literature and chemical composition of base metals. In general we can state these relations reflect the character of hardness change but are not reliable to calculate the actual hardness values. Relations relying on separate, definite measurement results ensure the reliable prediction of expectable hardness of heat affected zone at characteristic types of steel. Parameters at our disposal in the form of computer data bank, on the other hand, make the fast establishment of the necessary relations possible.

2. Structural changes in the heat affected zone of steel

Problems in connection with weldability are partly caused by changes in heat affected zone. Factors influencing them belong to three groups:

a) development of strain state
b) quality of austenite transformed phases
c) quantity of diffusable hydrogen content.

a) Strain state developing in welded joint is determined by the following:
- size of pieces to be welded
- rigidity of clamping
- shape, development of joint
- edge formation
- plate thickness
- yield point of base metal and weld metal
- welding technology (multi-pass welding, preheating, postweld heat treatment)

b) Determinant from the viewpoint of transformed phase:
  - chemical composition of steel
  - welding energy
  - thermodynamical characteristics of steel, joint development, heat extraction developing by the mass of the workpiece

c) Among others, the following influence the diffusable hydrogen content of the joint:
  - welding procedure
  - welding consumable
  - type of coating in case of hand arc welding
  - technological discipline

and other factors.

It means there are several factors to be taken into consideration in the course of technological planning.

3. Index numbers of weldability

Weldability cannot be judged in absolute index numbers, therefore reference to the characteristics of base metals and welding consumable is generally accepted. Characteristics of welded joint may significantly differ from the characteristics of base metal as a result of heat and other effects concomittant with welding thus breaking the homogeneity of steel unfavourable changes occur. Thermal cycle of welding is very important from the viewpoint of mechanical properties of heat affected zone. Heat flow of welding significantly differs from thermal cycle of heat treatment thus heat treatment TTT continuous cooling diagrams at our disposal are not suitable to state the characteristics of the heat affected zone. In accordance with Figure 1 welding thermal cycle is of shorter duration, higher temperature velocity of heating and cooling may differ by orders of magnitude from the thermal cycle

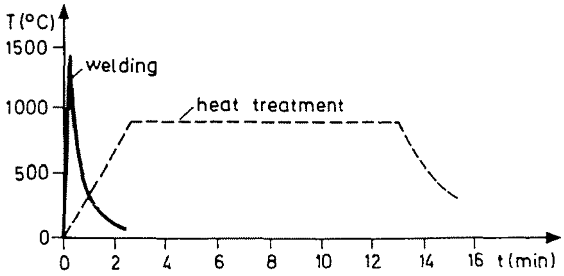

Fig. 1

of heat treatment. Homogeneous austenite structure does not develop in the whole heat affected zone during overheating. Figure 2 shows TTT continuous cooling diagrams [1], [3] made for different heat flows. Cooling curves belonging to identical hardness are in the figure and show the difference among developing structures well.

To characterize welding heat flow and cooling conditions cooling velocity or cooling time from 850 °C to 500 °C is used. Because of the decisive role of heat flow, the mechanical properties and structure of heat affected zone depend on cooling time. Yield point of the heat affected zone, tensile strength, hardness, elongation, contraction and impact energy of welded joints can be determined as a function of cooling time.

Out of the requirements in connection with welded joints, hardness has absolute index number. According to present prescriptions, hardness criterion can be given to the heat affected zone. In case of steel it is important how hardness changes as a function of cooling time and what cooling time can

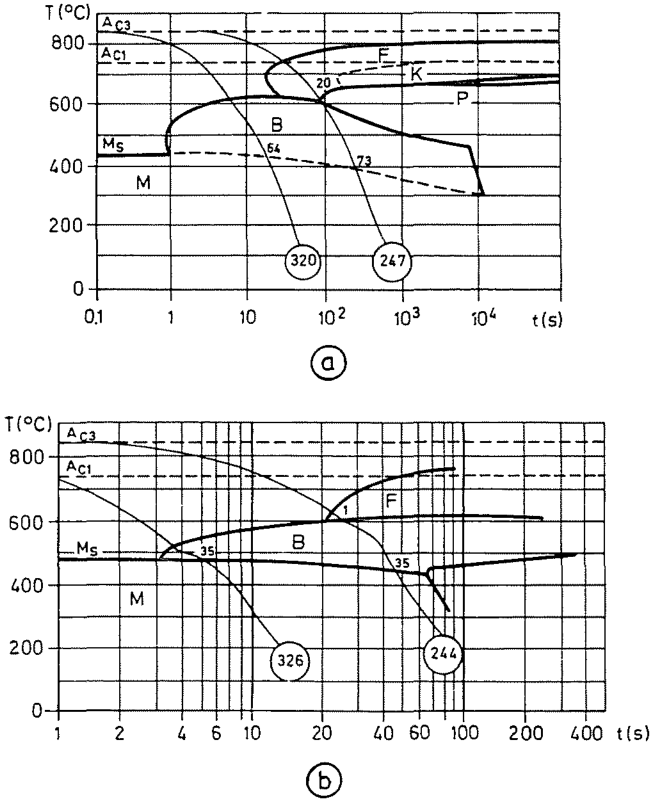

Fig. 2/a—b

avoid exceeding the prescribed hardness criterion. Hardness regarding its character changes according to Figure 3 [2]. A characteristic of the curve is the two asymptotes, in case of $\Delta t \rightarrow 0$ hardness tends to maximum hardness in steel, with the increase of Δt towards base metal hardness of normalized state. (Theoretically $\Delta t \rightarrow \infty$ would result in state of equilibrium but in practice it does not occur.)

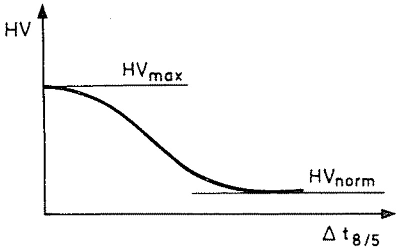

Fig. 3

Literature deals a lot with the determination of the curve. Some authors give equations describing whole relations [3]—[6], others introduce the determination of maximum hardness in steel [7]—[8].

4. Functions to describe hardness

4.1 Connection of hardness and composition

Relations for the determination of maximum hardness use the chemical composition of base metal. In the knowledge of chemical composition either the value of $HV_{\max}$ (2), or a carbon equivalent (7)—(10) is calculated. Assuming linear relation between carbon equivalent and hardness maximum relation of

$$HV_{\max} = A \cdot \mathrm{Ce} + B \tag{1}$$

form can be written. On this basis:

$$HV_{\max} = 90 + 1050 \cdot \mathrm{C} + 47 \cdot \mathrm{Si} + 75 \cdot \mathrm{Mn} + 30 \cdot \mathrm{Ni} + 31 \cdot \mathrm{Cr} \tag{2}$$

$$HV_{\max} = 939 \cdot \mathrm{C} + 284 \tag{3}$$

$$HV_{\max} = (823 \cdot \mathrm{C} + 300) \pm 33 \tag{4}$$

$$HV_{\max} = 666 \cdot \mathrm{Ce} + 40 \tag{5}$$

where:

$$\mathrm{Ce} = \mathrm{C} + \frac{\mathrm{Mn}}{6} + \frac{\mathrm{Mo}}{4} + \frac{\mathrm{Ni}}{40} + \frac{\mathrm{Cr}}{5} + \frac{\mathrm{V}}{14} + \frac{\mathrm{Si}}{24}$$

The relation suitable to calculate $HV_{\max}$ was looked for by the evaluation of maximum hardness measured on 167 low carbon steels. Looking for the equation in form (1) there are two possibilities:

1. Referring to the fact that maximum hardness in steel is given by martensite structure and the hardness of martensite is determined by carbon content it may be enough to take carbon content instead of carbon equivalent as the basis. Investigating $HV_{\max}$ measurement results as a function of C% the following regression equation is obtained:

$$HV_{\max}=(876.8\cdot \mathrm{C}\%+238.7)\pm 71.7 \tag{6}$$

2. It should be taken into account, however, that in case of $\mathrm{C}<0.2\%$ pure martensite structure cannot be produced. These types of steel in general cannot be hardened, in addition, part of low carbon content is bound in the form of carbide by carbide forming alloys. Therefore, other alloying elements are to be regarded in the form of carbon equivalent, too.

There are several methods to calculate carbon equivalent. Regarding them as basis to write relation (1) the following proved to be the best from the viewpoint of spreading range:

$$Ce_{\mathrm{IIW}}=\mathrm{C}+\frac{\mathrm{Mn}}{6}+\frac{\mathrm{Cr}}{5}+\frac{\mathrm{Mo}}{5}+\frac{\mathrm{V}}{5}+\frac{\mathrm{Ni}}{15}+\frac{\mathrm{Cu}}{15} \tag{7}$$

$$Ce_{\mathrm{WES}}=\mathrm{C}+\frac{\mathrm{Mn}}{6}+\frac{\mathrm{Si}}{24}+\frac{\mathrm{Ni}}{40}+\frac{\mathrm{Cr}}{5}+\frac{\mathrm{Mo}}{4}+\frac{\mathrm{V}}{14} \tag{8}$$

$$Pcm=\mathrm{C}+\frac{\mathrm{Mn}}{20}+\frac{\mathrm{Si}}{30}+\frac{\mathrm{Ni}}{60}+\frac{\mathrm{Cr}}{20}+\frac{\mathrm{Cu}}{20}+\frac{\mathrm{Mo}}{15}+\frac{\mathrm{V}}{10}+5\mathrm{B} \tag{9}$$

$$CEN=\mathrm{C}+A(\mathrm{C})\cdot\left[\frac{\mathrm{Si}}{24}+\frac{\mathrm{Mn}}{6}+\frac{\mathrm{Cu}}{15}+\frac{\mathrm{Ni}}{20}+\frac{\mathrm{Cr}+\mathrm{Mo}+\mathrm{V}+\mathrm{Nb}}{5}+5\mathrm{B}\right] \tag{10}$$

where:

$$A(\mathrm{C})=0.75+0.25\cdot \mathrm{th}\,20(\mathrm{C}-0.12)$$

The following regression relations were obtained for $HV_{\max}$ values that can be calculated from different carbon equivalents:

$$HV_{\max}=(488.1\cdot Ce_{\mathrm{IIW}}+183.5)\pm 91.5 \tag{11}$$

$$HV_{\max}=(478.2\cdot Ce_{\mathrm{WES}}+185.8)\pm 92.2 \tag{12}$$

$$HV_{\max}=(796.9\cdot Pcm+177.1)\pm 63.7 \tag{13}$$

$$HV_{\max}=(591.4\cdot CEN+155.8)\pm 77.6 \tag{14}$$

Investigating the measured values equivalents *Pcm* and *CEN* give the best approximation. In general, it can be stated that relations (11)—(14) give good values until limit $Ce<0.5$, exceeding this limit spreading is more and more significant. Repeating evaluation to range $Ce<0.5$ the equation having the smallest spreading (13) is the following:

$$HV_{\max}=(955.8\cdot Pcm+139.8)\pm 55.9 \tag{15}$$

In the range of greater carbon equivalent the extent of hardness increase is smaller. It is indicated by the fact that the multiplication factor indicating incline increased with the decrease of the constant member in the formulae obtained for low carbon equivalents. Relation (15) gives the most accurate value for the determination of hardness maximum at unalloyed steel of $C<0.2\%$ carbon content and microalloyed steel. Equation (6) ensures quick control for information.

Value $HV_{\text{normalized}}$ is also necessary to determine the relation between the hardness of heat affected zone and cooling time. If the measured hardness of normalized material is not known it can be determined with good approximation on the basis of the following formulae (16), (17). Tensile strength of plate of h mm thickness cooled from 920 °C at air [9] is:

$$\begin{aligned} R_m=9.81\{23+70\mathrm{C}+8\mathrm{Mn}+9.2\mathrm{Si}+7.4\mathrm{Cr}+3.4\mathrm{Ni}+\\ +5.7\mathrm{Cu}+32\mathrm{V}+54\mathrm{Ti}+46\mathrm{P}+[2.1-0.14\cdot(h-5)]\}\quad(\mathrm{MPa})\end{aligned} \tag{16}$$

The relation between the hardness and tensile strength of steel is the following:

$$255\ \mathrm{MPa}\le R_m\le 965\ \mathrm{MPa}$$

$$HV=0.31\cdot(R_m-255)+80 \tag{17.1}$$

$$965\mathrm{MPa}<R_m\le 2180\ \mathrm{MPa}$$

$$HV=0.5037\cdot(R_m-965)^{0.9213}+300 \tag{17.2}$$

4.2 Hardness-cooling time relation

In literature there are different hardness-cooling time relations. Figure 4 shows the different ways of the approximation of relation according to Figure 3 in summarized form. The simplest way of approximation is to assume linear relation (Figure 4a). A better approximation is a power function (Figure 4b) or a polynome of second degree (Figure 4c). From the viewpoint of cooling conditions it is expedient to describe the relation with exponential function (Figure 4d). Arc tangent function in Figure 4e and half bell curve in Figure 4f are adjusted to the asymptotes of the relation.

Taking the nature of the curve, the possible ways of its determination and boundary conditions into account, function relation was looked for in

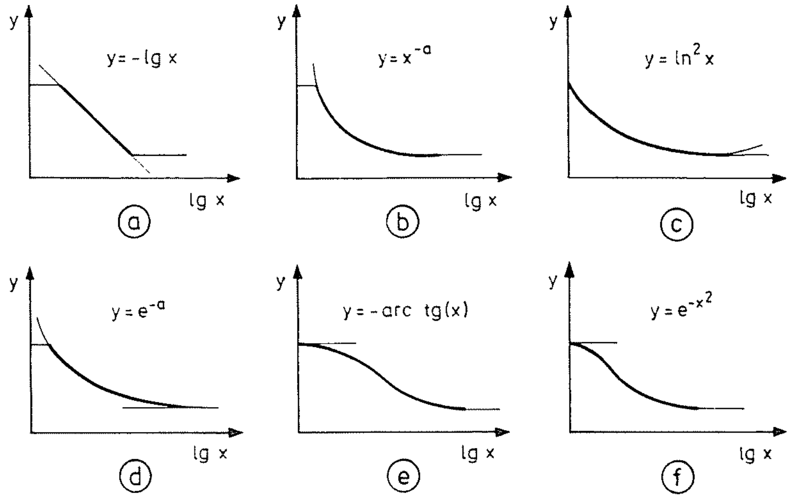

Fig. 4/a—f

the form $-\text{th}x$. The function suitable to describe the relation became of the following form:

$$HV = p_1 - p_2 \cdot \text{th}(\log_{p3} \Delta t_{8/5} - p_4) \qquad (18)$$

where p_1; p_2 are parameters determining asymptotes

$$p_1 = \frac{HV_{\text{max}} + HV_{\text{normalized}}}{2}$$

$$p_2 = \frac{HV_{\text{max}} - HV_{\text{normalized}}}{2}$$

p_3; p_4 are distortion parameters

The function tends toward $HV \to HV_{\text{max}}$ in case of $\Delta t \to 0$ and towards $HV \to HV_{\text{normalized}}$ in case of $\Delta t \to +\infty$. Determination of parameters p_1, p_2 in the knowledge of values HV_{max}, $HV_{\text{normalized}}$ is not difficult. These values can be obtained by experiments or relations (15), (16), (17) described earlier. To calculate variables p_3, p_4 the points of function $HV = f(\Delta t_{8/5})$ determined by experiment are necessary. Mathematically two measurement points are enough for the determination but the knowledge of 5—6 points in the transient range is by all means necessary for a function of acceptable accuracy. The parameters in question can be determined from measurement results by computer minimization.

Table 1 shows the results of this kind of parameter calculation with low carbon steel. The value of hardness maximum according to (6), (15), the

Table 1

	C	Si	Mn	S	P	Cu	Cr	Ni	Mo	V	Ti	Nb	Al	N
1.	0.15	0.26	0.86	0.029	0.019	0.13	–	–	–	0.026	–	–	–	0.017
2.	0.22	0.35	1.60	0.011	0.020	–	–	–	–	–	–	–	–	0.004
3.	0.16	0.28	1.43	0.022	0.020	–	–	–	–	0.1	–	–	–	0.003
4.	0.14	0.42	1.08	0.013	0.035	–	–	–	–	–	0.03	–	0.014	–
5.	0.19	0.43	1.34	0.024	0.022	0.1	0.1	–	–	0.13	–	–	0.019	0.011
6.	0.18	0.21	0.49	0.027	0.023	0.08	0.02	0.01	–	–	–	–	0.038	0.006
7.	0.16	0.18	0.46	0.025	0.020	0.15	0.09	0.06	–	–	–	–	0.042	–
8.	0.14	0.18	0.58	0.029	0.027	–	–	–	–	–	–	–	–	–
9.	0.09	0.32	1.61	0.020	0.017	0.07	0.03	0.03	–	–	–	–	0.002	–
10.	0.12	0.37	1.15	0.034	0.019	–	–	–	–	–	–	–	0.08	0.005
11.	0.18	0.47	1.24	0.029	0.029	0.17	0.1	0.06	–	–	–	–	0.024	0.008
12.	0.17	0.47	1.22	0.037	0.023	0.17	0.1	0.06	–	–	–	–	0.01	0.008
13.	0.14	0.43	1.16	0.030	0.018	0.18	0.12	0.07	–	0.037	–	–	0.012	0.01
14.	0.18	0.37	1.32	0.028	0.017	–	–	–	–	0.09	–	–	0.005	0.01
15.	0.16	0.41	1.35	0.017	0.016	0.02	0.03	0.01	–	–	–	0.03	0.009	0.005
16.	0.17	0.31	1.54	0.025	0.022	0.09	0.02	0.06	–	–	–	0.04	0.072	–
17.	0.13	0.28	1.4	0.023	0.028	0.13	0.13	0.57	0.03	0.012	–	0.02	0.19	–
18.	0.16	0.3	0.58	0.038	0.012	–	–	–	0.29	–	–	–	–	–
19.	0.092	0.34	0.05	0.024	0.005	–	–	–	–	–	–	–	–	–
20.	0.19	0.29	0.67	0.011	0.007	–	–	–	–	–	–	–	–	–

Table 2

	C%	Pcm	HV_{max} (C%)	HV_{max} [Pcm]	HV_{norm}	p_1	p_2	p_3	p_4
1.	0.15	0.2107	370	341	138	295	75	3.0636	2.0506
2.	0.22	0.3116	431	437	169	344	102	2.8888	2.3657
3.	0.16	0.2508	379	379	160	299	79	2.6849	2.2025
4.	0.14	0.208	361	338	148	288	68	4.8489	1.4537
5.	0.19	0.2943	405	421	175	330	105	2.3042	3.572
6.	0.18	0.2167	396	378	162	300	140	6.9635	0.4265
7.	0.16	0.202	379	350	168	260	120	8.9847	0.3069
8.	0.14	0.175	361	321	142	227	103	6.5348	1.0858
9.	0.09	0.1867	317	295	159	269	118	8.102	1.109
10.	0.12	0.1898	343	254	96	265	125	4.975	1.3859
11.	0.18	0.2722	396	311	109	330	119	4.1117	1.4522
12.	0.17	0.2612	387	302	107	330	130	4.9455	1.4783
13.	0.14	0.2322	361	273	100	290	120	4.3618	1.298
14.	0.18	0.2673	396	311	109	300	130	60.845	0.5348
15.	0.16	0.2438	379	292	104	287	106	4.205	1.5544
16.	0.17	0.2638	387	302	107	317	127	3.4827	1.7359
17.	0.13	0.235	352	264	98	329	108	2.9008	2.0911
18.	0.16	0.2183	379	292	104	350	180	8.498	0.4534
19.	0.092	0.1058	319	227	90	171	51	4.8004	1.6186
20.	0.19	0.2331	405	325	111	254	118	4.2634	1.4614

hardness of base metal of normalized state on the basis of (16), (17) and the parameters of function (18) were determined at different steel (Table 2). With the knowledge of the four parameters the hardness-cooling time relation is obtained. These parameters are suitable as the data of a computer data bank. Diagrams of functions determined by calculated parameters that are drawn by computer for the first five steels are in Figure 5.

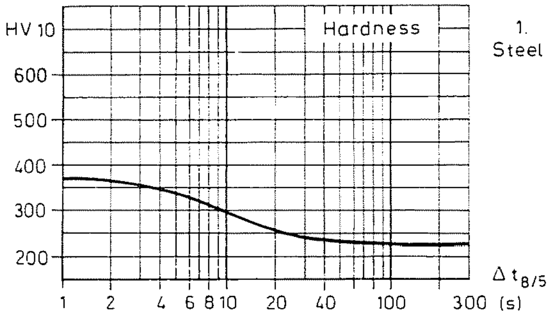

Fig. 5/a

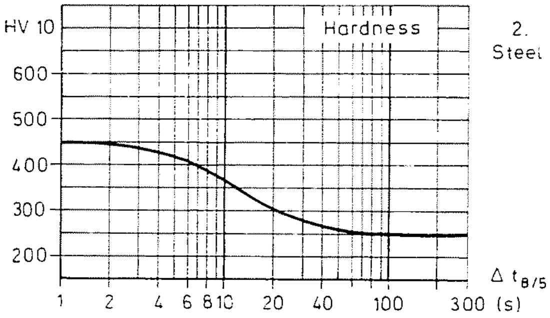

Fig. 5/b

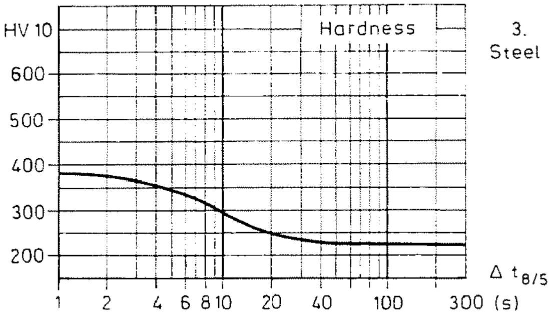

Fig. 5/c

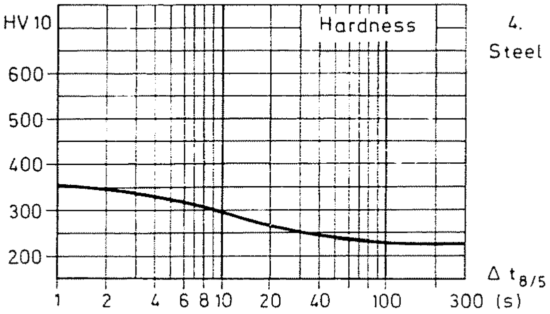

Fig. 5/d

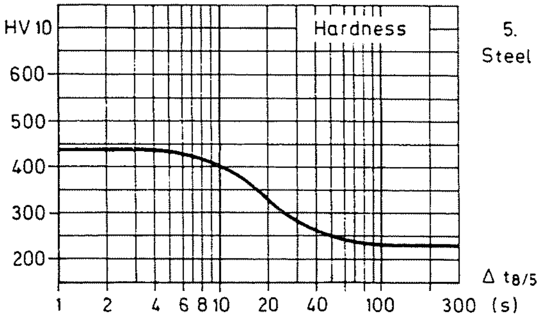

Fig. 5/e

Results, conclusions

1.

The mathematical formulae given in literature for the determination of hardness-cooling time relations were analysed and a four-parameter tangent hyperbolic function was set up by the author of the present study for the description of the above relations.

2.

To avoid the errors of general equations so far used for the determination of hardness-cooling time relations the application of equations established for the different types of steel individually was suggested. The method proposed is based on the calculative determination of the asymptotes of the function, on several experimental results, on theoretical considerations, furthermore on some practical measurements carried out on the type of steel concerned.

3.

The advantage of the method suggested over the relations of general validity is the increased accuracy and reliability of the results obtained.

4.

The small number of parameters used for function (18) assures the easy handling, the quick determination and the storage in a computer of the hardness-cooling time diagrams of low carbon steels.

5.

The present study describes the experimentally determined parameters of the hardness-cooling time relation of 20 types of steels of a different but given composition.

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