PREDICTION OF HEAT AFFECTED ZONE HARDNESS OF HSLA STEELS

Z. Zaczek *, J. Łabanowski *, J. Ćwiek *

A new formula has been developed for estimation of HAZ maximum hardness in HSLA steels. Experimental work was performed on five quenched and tempered steel grades with yield strength ranging from 440 to 780 MPa. The backward logistic curve was found to approximate HV_{max} versus cooling time $t_{8/5}$ in the best way.

INTRODUCTION

The cold cracking tendency depends on the structure of heat affected zone (HAZ), the hydrogen content in the weld and the stress concentration. Hardness may be taken as a simplified indicator characterizing the structure of a HAZ. Some authors give various methods for evaluating HAZ maximum hardness. Equations depend on chemical composition and cooling time. The methods proposed by Yurioka (1), Düren (2), Terasaki (3), Suzuki (4) seem to be more accurate than proposed by Beckert (5), Cottrell (6)) The above methods are based on various carbon equivalent formulae and often carbon content is added as another variable. These methods are valid only for definite range of chemical composition and specified welding procedure from which method is derived. However, the weld hardening characteristic curve HV_{max} versus cooling time between 800 and 500 °C ($t_{8/5}$), is approximated by some mathematical curves. The authors took up an investigation in order to find out a simple

* Technical University of Gdańsk, Poland.

method for practical application of evaluating maximum hardness in a HAZ of quenched and tempered HSLA steels produced in Poland.

EXPERIMENTAL PROCEDURE

Five industry quenched and tempered plates with 12 mm in thickness of steel grades 18G2A, 18G2AV, 15G2ANb, 10GHMBA and 14HNMBCu were used. The chemical composition of tested steels are presented in Table 1. The plates have yield strength ranging from 440 to 780 MPa. The bead-on-plate test was conducted with the use of SMAW process on 150x300 mm plates. At each plate there were seven padding welds each 150 mm long, made with low-hydrogen covered electrodes 4 mm in diameter. Various welding speeds gave nominal heat input of: 5, 10, 15, 20, 25, 30 and 40 kJ/cm. For each steel grade two preheating temperatures, 20 and 100 °C were used. Thermal histories and $t_{8/5}$ were measured by the use of Ni-NiCr thermo-couple. For each padding weld there were prepared two samples for hardness test. The hardness measurement was carried out by the Vickers method with 10 kg load along the fusion line in coarse region of the HAZ.

EXPERIMENTAL RESULTS AND DISCUSSION

Table 2 shows measured cooling times $t_{8/5}$ for a range of heat inputs and preheating temperatures. Typical example of relationship between cooling time and HAZ maximum hardness is presented in Figure 1. The description of each set of HAZ maximum hardness depending on cooling time was approached with the use of an exponential curve, a backward logistic curve (4), and an arc-tangential curve (1). The best correlation between HV_{max} and cooling time $t_{8/5}$ was obtained from the backward logistic (BL) curve in the form:

$$HV_{max} = HV_B + \frac{HV_M - HV_B}{1 + \exp\left(\frac{t_{8/5} - a}{b}\right)} \qquad (1)$$

where: $HV_B = HV_{max}$ at $t_{8/5} = 70$ sec

$HV_M = HV_{max}$ at $t_{8/5} = 2$ sec

a, b – curve constants depending on chemical composition of steel

Figure 1 shows an example of the BL curves for 18G2A and 14HNMBCu steels. The value "a" is the distance of the center of symmetry of BL curve from the vertical axis of a diagram. The value "b" characterizes the slope of BL curve at the center of symmetry in the form:

$$\tan\alpha = \frac{HV_M - HV_B}{4b} \qquad (2)$$

Table 3 shows data of the tested steels like average values of HV_M and HV_B observed in the HAZ and calculated by the equation (1), the factors of BL curves "a" and "α", correlation coefficients of BL curves. The CE_{LD6} is carbon equivalent proposed by Düren (7) for a short cooling time $t_{8/5}$ = 6 sec.

The characteristic slope of the curves presented in Figure 1 can be easily explained if we consider the effect of cooling time on the amount of martensite in the HAZ. The curve can be divided into three characteristic parts. The upper part of nearly fixed maximum hardness represents a structure of 100 % martensite, where critical cooling rate is applied. The mixed structure of martensite and bainite occurs in the middle part of the curve. When the cooling time represented by this part of the curve increases, the amount of martensite decreases with the simultaneous decrease of the hardness. Once the structure in the HAZ consist of 100 % bainite the hardness represented by the lower part of the curve becomes almost constant. The max hardness of the structure with 100 % martensite is almost constant, independent of the cooling time. As it can be seen in Table 3 with the increase of carbon content the HAZ maximum hardness also increases. This confirms the generally accepted opinion, that the martensite hardness of low-alloy steels depends only on carbon content. The hardness of the structure with pure bainite is almost constant, independent on the cooling time. The maximum hardness of bainite grows with the increase of carbon equivalent as compared to martensite hardness (cf. Table 3). In the mixed structure of martensite and bainite, the proportion of these constituents depends not only on the chemical composition but also on the cooling time.

As it can be seen in Table 3 the HV_{max} versus cooling time $t_{8/5}$ curve can be quite accurately approximated by the backward logistic curve. The characteristic material constants HV_B, HV_M, "a" and "b", which define the BL curve can be determined by means of a simple regression analysis of measured HV_{max} values. The correlation coefficients of investigated steels range from 0.93 to 0.97.

Table 3 shows that with the growth of carbon equivalent the distance of the center of symmetry of BL curve from the vertical axis increased. Thus, at longer cooling time we obtain 50 % of martensite and 50 % of bainite in the HAZ.

The BL curve for 14HNMBCu steel has a well developed upper part. For the lower carbon equivalent, the distance of the center of symmetry of BL curve is smaller. This results in the lowering or even the lack of the upper part of the curve (cf. Figure 1, 18G2A steel). We could see here the great difference between the calculated and measured HV_{max} - since the cooling time applied in the experiment was too long we did not obtain 100 % martensite in the HAZ structure.

Table 3 shows that with the growth of preheat temperature the distance of the center of symmetry increased:the bigger the carbon equivalent the greater the distance. With the growth of preheat temperature the slope angle of the BL curve at the center of symmetry decreased. This can be a proof for the increase of the range of cooling time within which the mixed structures arise.

CONCLUSIONS

1. The HV_{max} versus the cooling time $t_{8/5}$ hardness characteristic curve can be approximated with satisfactory accuracy by the backward logistic curve. This equation can be used for making accurate predictions of the HAZ maximum hardness of HSLA steels with CE_{LD6} from 0.26 to 0.40, at welding in the form of a single bead with the preheat temperature 20 or 100°C, and the cooling time from 1 to 130 sec.
2. With the decrease of carbon equivalent of the low alloy steels we can observe a decrease of $t_{8/5}$ at which we obtain the mixed structure of 50 % martensite and 50 % bainite in the HAZ (the center of symmetry of the BL curve).
3. With the increase of preheat temperature we also obtain an increase in the the cooling time $t_{8/5}$ at which we obtain the mixed structure of 50 % martensite and 50 % bainite. The bigger the carbon equivalent the greater the growth of cooling time $t_{8/5}$.

REFERENCES

(1) Yurioka, N., et al, Metal Constr., Vol.19, No.4, 1987, pp. 217R-223R.

(2) Lorenz, K., Düren, C., Mannesmann Forschungsberichte, No.920, 1982, pp. 1-11.

(3) Terasaki, T., Akiyama, T. and Serino, M., "Chemical Compositions and Welding Procedure to Avoid Cold Cracking", Proc. Int. Conf. "Joining of Metals". April 15-18, 1984. Helsingor. Denmark. pp. 381-386.

(4) Suzuki, H., Trans. of Japan Weld. Soc., Vol.16, No.2, 1985, pp. 61-68.

(5) Beckert, M., Holz, R., Schweisstechnik. Vol.23, No.8, 1973, pp. 344-346.

(6) Cottrell, C., Metal Constr., Vol.16, No.12, 1984, pp. 740-744.

(7) Düren, C., 3R Int., Vol.24, No.8, 1985, pp. 3-7.

TABLE 1 - Chemical Composition of Tested Steels.

Steel grade	Chemical composition, weigth %								
	C	Mn	Si	Cr	Ni	Cu	Mo	V	B
14HNMBCu	.19	.73	.25	.64	.70	.29	.50	.09	.004
10GHMBA	.08	.76	.31	1.05	.25	.30	.50	.05* .035**	.005
18G2A	.16	1.39	.33	-	-	-	-	-	-
15G2ANb	.18	1.36	.32	-	-	-	-	.035**	-
18G2AV	.18	1.36	.41	-	-	-	-	.08	-

* - Ti, ** - Nb

TABLE 2 - Coling Times $t_{8/5}$ in Bead-on-plate Test.

Preheat temperature	$t_{8/5}$ in sec at heat input in kJ/cm						
	5	10	15	20	25	30	40
20 °C	1.1	4.4	10.0	17.8	27.8	40.0	71.1
100 °C	2.0	8.0	17.9	31.8	49.7	71.6	127.2

TABLE 3 - Factors of the BL Curves for Tested Steels.

Steel grade	C %	CE_{LD6}	T_0 °C	HV_M		HV_B		a_s	α	R
				obs.	cal.	obs.	cal.			
15G2ANb	.18	.289	20	468	494	227	218	18	81°58'	.961
			100	453	474	227	203	35	72°44'	.967
18G2A	.16	.263	20	428	450	220	215	17	81°55'	.973
			100	428	455	220	218	20	75°01'	.951
18G2AV	.18	.299	20	458	465	239	223	22	77°18'	.933
			100	437	469	239	235	22	75°08'	.963
10GHMBA	.08	.315	20	381	382	290	230	46	78°21'	.955
			100	379	378	290	226	80	63°13'	.936
14HNMBCu	.19	.398	20	490	489	318	303	42	83°17'	.951
			100	477	482	318	301	74	71°03'	.935

T_0 - preheat temperature, R - Correlation coefficient

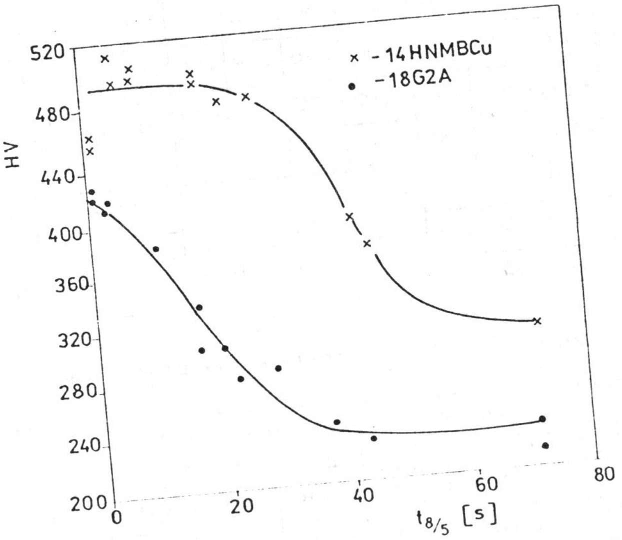

Figure 1 HAZ maximum hardness characteristic curves