ESTIMATION OF WELD METAL HARDNESS OF Cr-Mo STEELS

By

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ABSTRACT

Hardness variation in the Cr-Mo steel weld metal as a function of Cr content and weld cooling rate was studied Chromium in the weld metal was varied by adding known amount of high purity Cr into the weld pool produced by a stationary arc. The cooling rate of the weld was measured by plunging W-Rh thermocouple in to the weld pool just at the time of extinguishing the arc and measuring the variation in temperature as a function of time using a X-t recorder. The microstructural studies revealed that in the low Cr steels the structure varied from fully martensitic to a mixture of bainite and martensite as the weld cooling rate decreased while for weld metal with Cr content higher than 5 wt% the structure remained fully martensitic irrespective of the cooling rate. The measured hardness of the weld metal for different Cr contents and cooling rates was compared with that predicted by Yurioka's and Hart's formulae. It was found that Yurioka's formula can be used to predict the hardness of the weld metal with reasonable accuracy. It was further noticed that there is a reduction in the maximum hardness at Cr content above 5wt% and it is attributed to the presence of delta ferrite in the weld metal.

INTRODUCTION

Cr-Mo steels are widely used in power plants and petrochemical industries for applications involving high temperature. In the normalised condition, microstructure of these steels varies from ferritic to martensitic depending on the alloy content (1). For weld metal, especially in the case of low Cr steels, the heat input also influences the final microstructure. There would be a corresponding variations in the mechanical properties which are reflected in the hardness of the weld metal. Hence, hardness can be used to predict the mechanical properties of the weld metal in the as welded condition. Further, these steels are susceptible to weld metal hydrogen assisted cracking (HAC); and therefore, weld metal hardness along with diffusible hydrogen content can be used to determine the minimum preheat temperature required to prevent HAC in the steels using empirical formulae available in literature (2,3).

However, very few studies have been carried out to estimate the weld metal hardness and establish its correlation with the mechanical properties and the HAC susceptibility of the weld metal. This is in contrast to the extensive studies carried out to predict the maximum HAZ hardness of various carbon and HSLA steels. The hardness of the HAZ or weld metal depends on both the chemical composition and the cooling rate. The chemical composition is best represented by a parameter called Carbon Equivalent (CE) (4). Different formulae to calculate CE for different range of composition of steels are available in the literature. For predicting weld metal hardness Hart (3) has suggested the following formula obtained from the regression analysis of the data obtained from wide range of steels studied.

$$HV = 427.5\ CE_H + 2028 \qquad (1)$$

where

$$CE_H = C + 0.09\ Mn + 0.05\ Ni + 0.08\ Cr + 0.09\ Mo - 0.018t_{8/5}$$

and $t_{8/5}$ is the cooling time from 800 to 500°C.

However, the range of composition studied by Hart covers Cr-Mo steels containing less than 2 wt% Cr only. The microstructure of the weld metal of these steels is predominantly bainitic or ferritic and hence, this formula may not be applicable to steels where the as welded microstructure is predominantly martensitic as in the case of 9Cr-1 Mo steels. Among the large number of formulae available in literature to predict the maximum HAZ hardness, Yurioka's latest formula was found to be applicable to a wide range of composition including Cr-Mo steels containing a maximum or 9 wt% of Cr (5). Yurioka found that a typical hardness v/s $t_{8/5}$ curve consists of an upper saturation value corresponding to fully martensitic structure and a lower saturation value corresponding to fully non-martensitaic structure. He fitted the data pertaining to the variation in hardness with increasing $t_{8/5}$ between these two values to an arc tangential curve and derived the following equation for boron free steels containing less than 0.3 wt% of carbon.

$$H_{max} = 220 + 442\ C(1 - 0.3(C^2) + \tanh(Y) + \{68 + 402\ C(1 - 0.3C^2) - 59\tanh(Y)\}\ \arctan(X) \quad \ldots\ldots (2)$$

where

$$X = \{\log(t_{8/5}) - 2.30CE_I - 1.35\ CE_{III} + 0.882\}/\{1.15\ CE_I - 0.673CE_{III} - 0.601\}$$

and

$$Y = 2.65\ CE_{II} - 0.690$$

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

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

$$CE_{III} = C + Mn/3.6 + Cu/20 + Ni/9 + Cr/9 + Mo/9$$

It may be seen that the equation contains three different CE values. Out of this CE_I, is used to determine the maximum value of $t_{8/5}$ below which the structure is fully martensitic, CE_{II} to calculate the hardness of the non-martensitic structure and CE_{III} to find out the value of minimum cooling time above which the structure does not contain any martensite. Yurioka applied this formula to predict the HAZ hardness of large number of steels and fairly good correlation has been obtained. The validity of this formula for a wide range of low carbon micro alloyed steels has been confirmed by Lundin et.al (6). However, application of this formula to predict the weld metal hardness has not been reported so far.

In the present study, hardness of Cr-Mo steel weld metals, differing in Cr content and produced at different $t_{8/5}$ were measured and correlated with the microstructure. It was found that Yourioka's formula to predict the maximum HAZ hardness can be used to predict the weld metal hardness of these steels.

Experimental

A 12 mm thick 2.25 Cr-1Mo plate containing 0.118 (wt%) C, 2.184 (wt%) Cr, 0.998 (wt%) Mo, 0.246(wt%) Si, 0.463(wt%) Mn and 0.161(wt%) Ni was used in the present study. Bead-on-plate welds with varying heat inputs were made on the plate using autogenous GTAW process and cooling curves for each weld were obtained by measuring the temperature variation as a function of time using W-Rh thermocouple which was plunged into the molten weld pool. From this $t_{8/5}$ for each weld was measured. Heat input was varied by either changing the current or the welding speed.

Composition of the weld pool was varied by adding Cr into the molten weld pool produced by the stationary arc. A weld pool was produced at the centre of the sample of dimensions 50x50x12 mm by striking the welding arc of current 150 amps and voltage 17 volts for 60 secs. Assuming that the weld pool is hermispherical, amount of Cr to be added to increase the Cr content of the molten metal to 3, 4, 5 and 7 (wt%) was calculated and added to the weld pool while the arc was on. A schematic of the Cr addition into the weld pool is shown in **Fig. 1.** After homogenizing and cooling the weld pool, arc was struck again at the same spot for different durations to obtain weld metal cooled at different $t_{8/5}$. Cooling curves were obtained by plunging the thermocouple just at the time of extinguishing the arc.

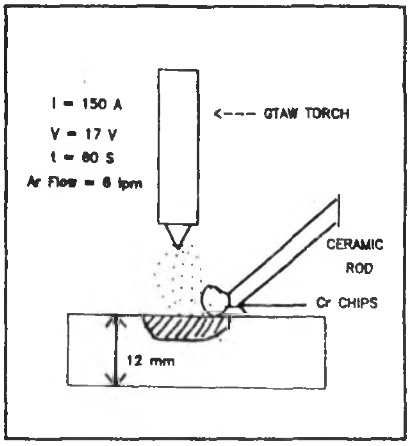


Fig. 1 : Schematic representation of addition of Cr into the molten weld metal

The weld metal was etched using Vellela's reagent or Nital to reveal the microstructure. Microstructural variations with change in heat input and Cr content were studied. Hardness of the weld metal was measured at 10Kg load using Vickers hardness tester. The actual Cr content in the weld pool was analysed using atomic absorption spectrophotometry.

RESULTS AND DISCUSSIONS

2.25Cr-1Mo Steel

Cooling curves obtained for bead-on-plate welds made at five different heat inputs are shown in **Fig. 2**. The $t_{8/5}$ values were measured from

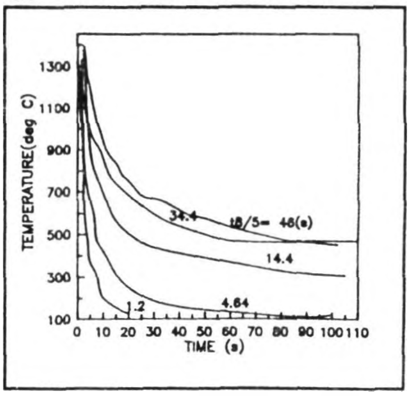
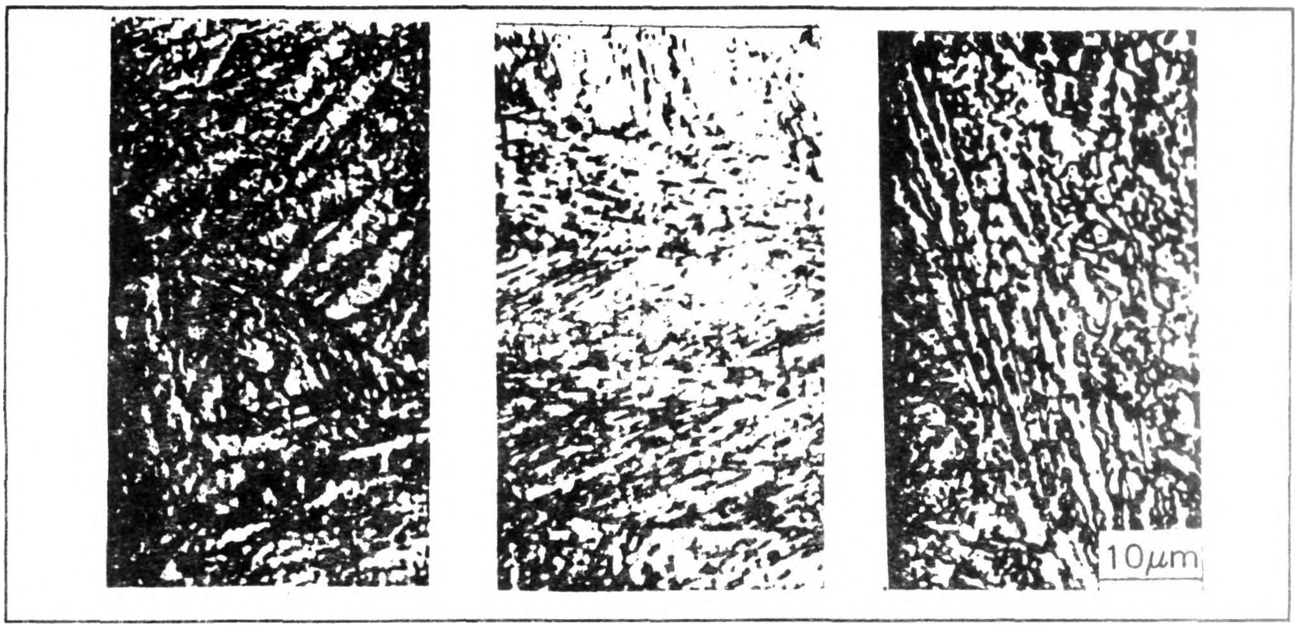


Fig. 2 : Cooling Curves for different bead-on-plate welds with corresponding $t_{8/5}$ values



(a) (b) (c)

Fig. 3 : Microstructure of bead-on-plate welds of 2.25Cr-1Mo steels with $t_{8/5}$ values, (a) 3 s., (b) 12 s., and (c) 46 s.

these curves and are indicated along with the cooling curve. The weld with maximum $t_{8/5}$ was obtained by preheating the plate to 423 K. With increase in heat input more than proportionate increase in the value of $t_{8/5}$ is observed.

Microstructures of three bead-on-plate weld metals having different $t_{8/5}$ values are shown in **Fig. 3**. The structure is fully martensitic at lower $t_{8/5}$ while it is predominantly bainitic at higher $t_{8/5}$. In the intermediate values of heat input it is a mixture of bainite and martensite. Microstructure of the weld metal produced using stationary arc too varied from martensitic to bainitic with increase in $t_{8/5}$.

Hardness of the weld metal as function of $t_{8/5}$ for both the bead-on-plate weld and stationary arc weld are shown in **Fig. 4**. The hardness variations in both the cases are almost identical, indicating that the weld metal produced by stationary arc method can be used to study the variation in the hardness of the weld metal cooled at different cooling rate. The advantage of this technique is that the cooling time can be varied by changing the time of arc and the alloy content by addition of alloying elements into the molten weld pool.

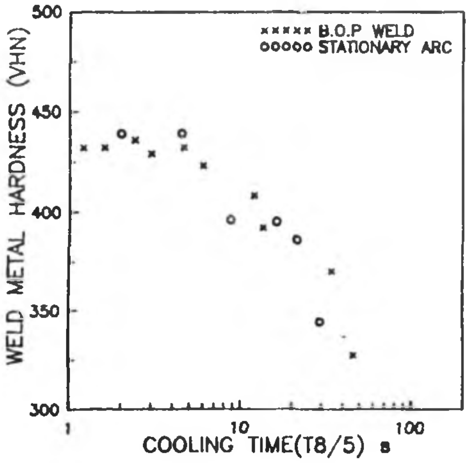
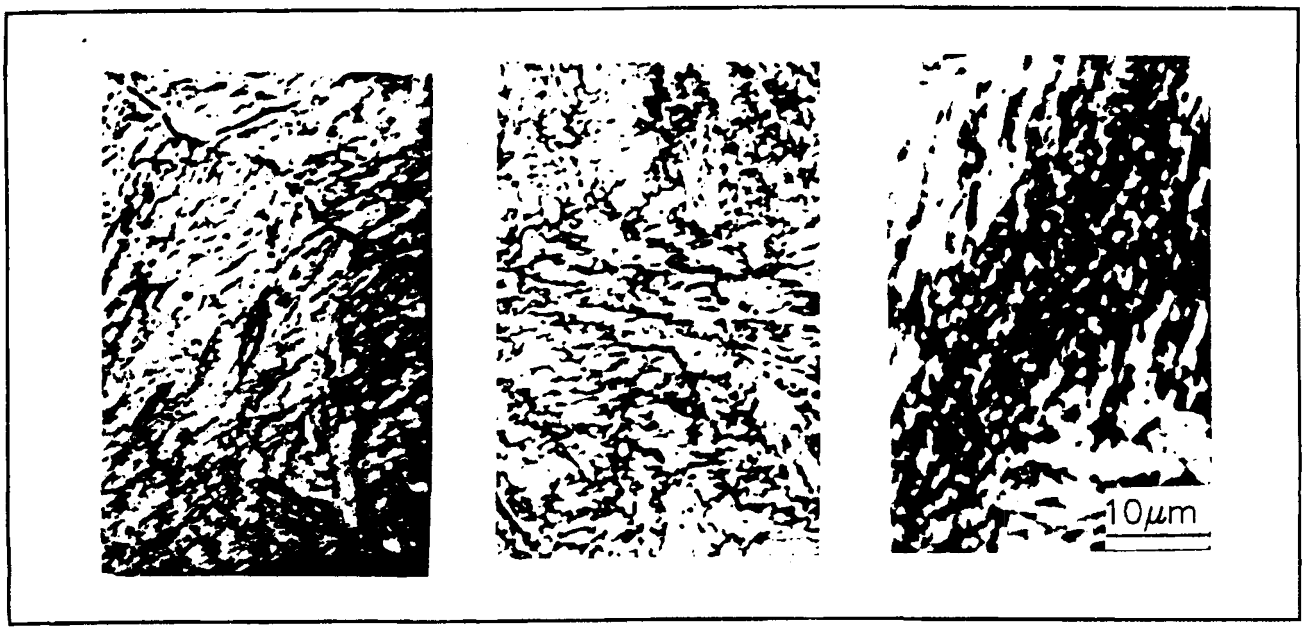


Fig. 4. : Variation in weld metal hardness with $t_{8/5}$ for 2.25 Cr-1Mo steel weld metal.

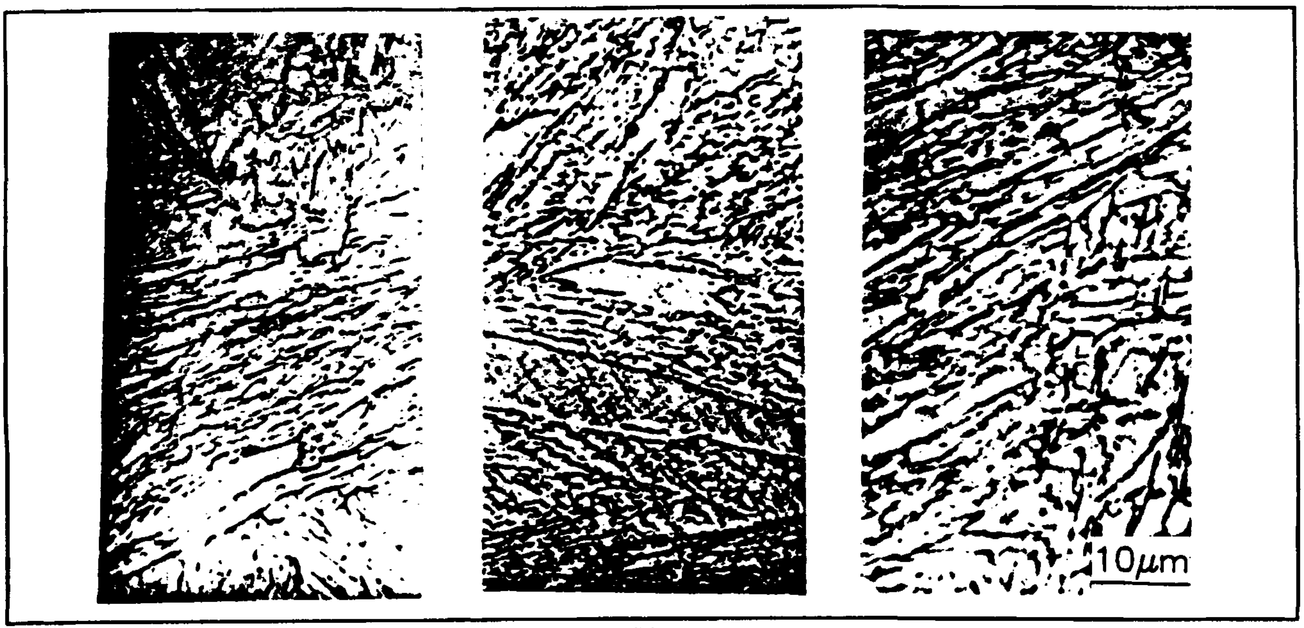
Weld Metals with Cr Addition

The microstructures of the weld metals produced at three different cooling times to which Cr additions are made to increase the Cr content to 3, 5 and 7 wt% are shown in **Fig. 5, 6, and 7** respectively. In Fig. 5, it can be seen that the structure is fully martensitic for weld with $t_{8/5}$ value of 3.2s while it is a mixture of bainite and martensite for weld with $t_{8/5}$ of 29.4 sec. In Fig. 6, the structure is fully martensitic for all the cooling times shown. All the structures shown in Fig. 7 are also martensitic, though traces of δ ferrite can also be seen.



(a) (b) (c)

Fig. 5 : Microstructures weld metals with 7 wt% Cr and having $t_{8/5}$ values of (a) 3.2 s., (b) 16.2 s. and (c) 29.4 s.

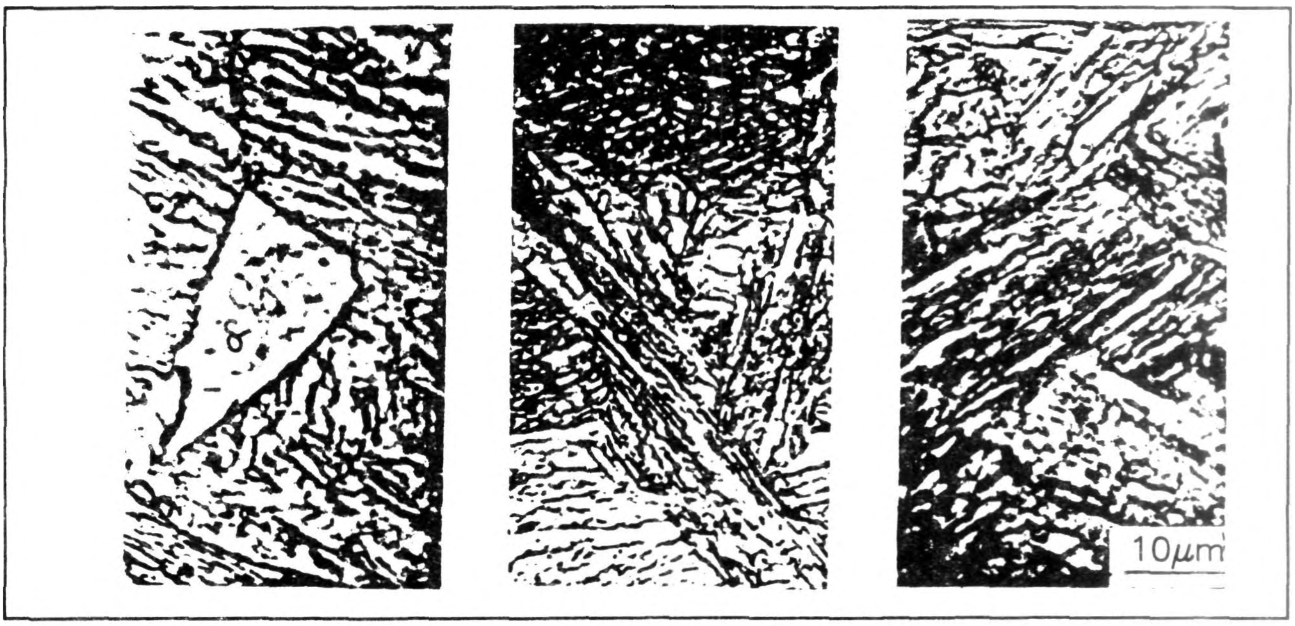


(a) (b) (c)

Fig. 6 : Microstructures weld metals with 5 wt% Cr and having $t_{8/5}$ values of (a) 3.2 s., (b) 21.4 s. and (c) 29.4 s.

Thus results of microstructural studies indicate that the structure of the weld metal containing more than approximately 5wt.% of Cr is martensitic irrespective of the heat input used for welding while that of weld metal with lower Cr content varies form fully martensitic to bainitic as the heat input increases.

Variation in the hardness of the weld metals as a function of heat input and the Cr content is shown in **Fig. 8**. The variation in hardness is greater for weld metal containing low wt.% of Cr, than those containing high wt.%. Above 5wt.% of Cr the hardness is practically independent of the cooling time. This is in agreement with the microstructural obser-



(a) (b) (c)

Fig. 7 : Microstructures weld metals with 7 wt% Cr and having $t_{8/5}$ values of (a) 3.2 s., (b) 16.2 s. and (c) 29.4 s.

vation that the weld metal with higher wt.% Cr contain only martensite even at higher $t_{8/5}$ values. However, for weld metal with 7wt.% of Cr, it was found that though the hardness was independent of $t_{8/5}$, it was found to be lower than the maximum hardness observed for the other weld metals. Though exact reason for this is not clear, it may be attributed to the presence of delta ferrite in the weld metal. The actual amount of Cr in the weld metal is analysed and a three dimensional plot showing the variation of hardness as function of wt.% of Cr and $t_{8/5}$ is shown in **Fig. 9**.

The maximum weld metal hardness was calculated using formulae proposed by Hart (equation 1) and Yurioka (equation 2). For 2.25Cr-1Mo weld metal, the maximum hardness predicted using Hart's formula is only 380 VHN as against the measured value of 432 for highest cooling rate. Similarly for a $t_{8/5}$ value of 35 s. the predicted hardness is only 152 VHN while the measured value is 370 VHN. This shows that the formula proposed by Hart cannot predict the hardness of even 2.25Cr-1Mo steel and hence cannot be used for estimation of hardness in Cr-Mo steel weld metal used in this study.

The correlation between the measured hardness and predicted by Yurioka's formula was much better than that obtained in the case of Hart's formula. A comparison of the measured and predicted values are given in **Fig. 10.** This suggests that Yurioka's formula can be used to predict the weld metal hardness of this class of steels with reasonably good accuracy. Regression analysis of the data gave an R^2 value of 0.83 which is in the same range as that obtained for the data used by Yurioka. Yurioka's formula also predicts that the structure of the weld will be martensitic without ferrite or bainite if the Cr content in the steel

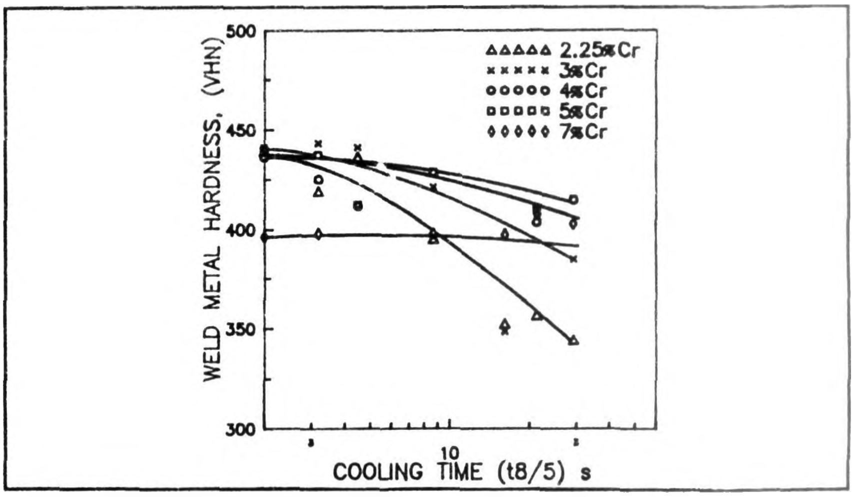


Fig. 8 : Variation of hardness in Cr-Mo steel weld metals with $t_{8/5}$.

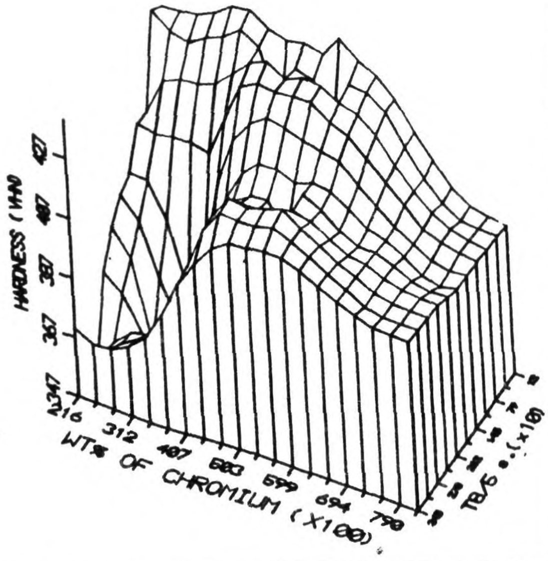


Fig. 9 : Three dimensional representation of hardness variation in Cr-Mo steel weld metal as a function of wt% Cr and $t_{8/5}$.

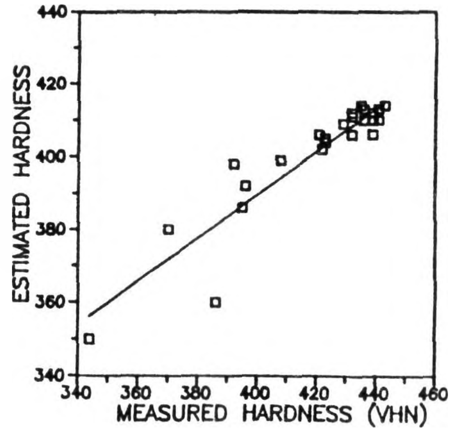


Fig. 10 : Comparison of measured hardness and that estimated by Yurioka's formula

is above 5wt.%, for a wide range of cooling times that is usually experienced during welding.

Any attempt to predict the maximum hardness of Cr-Mo steels should consider the observed reduction in hardness at Cr content higher than 5wt.%. One of the reasons for this reduction is the presence of delta ferrite that may be formed and retained in the weld metal during the weld thermal cycle. The tendency for a steel to retain delta ferrite during welding is determined by its composition which is in turn represented by a term called Cr_{eq} (7). Above certain value of Cr_{eq}, the volume fraction of δ-ferrite increases with Cr_{eq}. Since hardenability of the steels with high Cr content is sufficiently high, the microstructure of the weld contains, in addition to a small volume fraction of delta ferrite, only martensite with no bainite or ferrite. Thus increase of Cr content would result only in the reduction of hardness due to increased volume fraction of δ ferrite. Thus, it is clear that the hardness does not increase linearly with Cr content and hence any equation which shows linear relationship between hardness and Cr content would be of limited validity. In this context it may be seen from **Fig. 10** that Yurioka's formula gives good estimation of hardness at higher Cr levels. A closer look at the equation would show that the value of CE_1, doesn't vary linearly with Cr wt.% but as a function of cr $(1-0.16\sqrt{Cr})$ which indicates that at higher Cr levels the contribution of Cr to CE_1 is lower than at lower Cr levels. This in turn means a lower contribution to estimated harndess from Cr thus a better fit with the measured hardness than the equations which consider only linear increase of CE with Cr.

From the above discussions it is clear that though Cr increases hardenability of the Cr-Mo steels, it doesn't contribute to a corresponding change in the weld metal hardness. In fact it was found that the maximum hardness obtained in the case of higher Cr weld metal is lower than that obtained in the lower Cr weld metal. Though Yurioka's formula predict the weld metal hardness with reasonable accuracy, it doesn't address the metallurgical reasons for the observed phenomena. Since presence of δ ferrite is one of the reasons for lower hardness, and its volume fraction is predicted by the concept of Cr_{eq}, it may be necessary to use this parameter also for the prediction of hardness in this class of steels. Further studies involving Cr-Mo steels of different compositions are in progress to derive a simple and reliable equation to predict the weld metal hardness in this class of steels.

CONCLUSIONS

The major conclusions from the present study are the following,

1. The microstructure and hardness of the weld metal of low Cr steels vary with heat input.
2. As the Cr content increases, these variations become less dependent on the heat input and in steels with Cr higher than 5wt.%, weld metal structure is

martensitic and neither the structure nor the hardness vary with heat input.

3. A reduction in the hardness of the weld metal at 7wt.% Cr is observed probably due to the presence of delta ferrite in the weld metal

4. Yurioka's formula to predict maximum HAZ hardness can be used to predict the weld metal hardness of this class of steels with reasonable accuracy.

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