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Towards a prediction of the hardness of the heat-affected zone of steel weldments

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The prediction of the level of hardness developed in the heat-affected zone (HAZ) of steel welds is discussed. It is composed of a thermal model that predicts the cooling behaviour from input welding parameters and a material model for calculating the HAZ hardness as a result of weld cooling. Experimental investigations were carried out on eight different steel welds using three different electrodes under two different welding processes. Comparisons of the experimental results as well as the experimental results reported in the open literature, against the calculated values for both HAZ hardness and cooling time, were conducted. The results presented in this paper show good agreement between calculated and measured values of both cooling rate and hardness. The calculations can be carried out readily in small pocket-sized computers.

1. Nomenclature

a, b, N	constants
d	heat transfer coefficient
h	thickness (m)
τ	time (sec)
t_r	non-dimensional thickness parameter
v	welding speed ($\mathrm{m\,sec^{-1}}$)
$(C_{eq})_{Terasaki}$	carbon equivalents in the Terasaki model
$(C_{eqI}, C_{eqII})_{Yurioka}$	carbon equivalents in the Yurioka model
C_p	volumetric specific heat capacity ($\mathrm{J\,m^{-3}\,°C^{-1}}$)
H	hardness in VPN
$H(\tau_{mo})$	hardness value corresponding to 0% martensite in VPN
$H(\tau_{m100})$	hardness value corresponding to 100% martensite in VPN
I	current (A)
K	thermal conductivity ($\mathrm{W\,m^{-1}\,°C^{-1}}$)
Q	net heat input rate (W)
T	temperature (°C)
T_0	preheat temperature (°C)
V	voltage (V)
η	weld efficiency
τ	cooling time between 800 and 500 °C (sec)
τ_{mo}	cooling time between 800 and 500 °C corresponding to 0% martensite transformation (sec)
τ_{m100}	cooling time between 800 and 500 °C corresponding to 100% martensite transformation (sec).

2. Introduction

Hardness and strength of the heat-affected zone (HAZ) has long been held an important weldability parameter. In general the higher the hardness of the coarse-grained region (adjacent to the fusion zone) of the HAZ, the greater the likelihood of the formation of so-called "cold-cracks" in this region. These are cracks that form as the weld cools and reside in the HAZ even before the section is put into service. So important is this problem in fabrication practice that the term "weldability" is, by and large, synonymous with the HAZ cold-cracking susceptibility of a material. In as much as cold crack formation must be avoided in service, HAZ hardness is often limited by specification [1, 2]. The hardening allowed in the HAZ depends on several factors: the hydrogen level (determined by the welding process used), joint preparation and work-piece thickness, and most importantly, the metal composition, specifically the equivalent carbon content. Critical hardness level range from about 250 VPN where various factors contributing to the risk of cracking are all unfavourable, to 500 VPN, where welding conditions are more favourable. The British Welding Institute document "Welding Steels without Hydrogen Cracking" is an excellent guide on this subject [3].

In addition to cold crack formation, the sensitivity of the HAZ to corrosion is hardness dependent. Where corrosion is a potential problem, HAZ hardness specifications are more severe than the hardness

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limits imposed for those situations where HAZ cold cracking is the danger. In view of the foregoing arguments, there is an obvious need in design and fabrication practice for a reliable method of calculating HAZ hardness levels. There are some semi-empirical materials models available in the literature for this purpose [3–9]. However, they are all based on regression analysis from experimental data and there is no fundamental reason to choose one or another.

The problem of predicting hardness of the heat-affected zone due to the welding process is a complex one, because the weldment presents a three-dimensional geometry with temperature-dependent elastic–plastic, stress–strain behaviour. A three- dimensional computational analysis, such as a finite element analysis for the welding procedure, would be costly for a single analysis and thus difficult to use to study a wide range of parameters. Thus a more simplified analytical model is appropriate. The purpose of this paper is three-fold: first to present a simple computational method designed to predict the HAZ hardness of steel weldments; second to describe welding experiments and the resulting hardness data; third to present comparisons between the hardness predicted by the computational model and the experimental data. These comparisons help to evaluate the ability of the computational model to predict the HAZ hardness.

3. Heat affected zone hardness models

Although all models available for calculating HAZ hardness are relatively independent, they are, nevertheless, all based on the same basic principles. It is said that for each steel there exists a "characteristic hardness curve" such as that shown schematically in Fig. 1 [7]. The characteristic hardness curve is considered to be unique for a given composition, while all welds (e.g. shallow arc weld (SAW), deep penetration electron beam or laser welds, tee joint configuration, etc.) that have the same cooling time will have, in principle, the same HAZ hardness. It is apparent that this is an approximation, because the structure of the weldments is determined by the entire cooling history and not just the 800 to 500 °C cooling time, as reported in the open literature [7, 8]. Nevertheless this is a reasonable approximation for most welding practice [7–9] and is therefore widely used.

Material models for generating the characteristic hardness curve have been proposed [2, 4–9]. The method reported by Stout *et al.* [2] is experimentally based and is therefore not suitable for computer implementation. Other models reported [4, 5] are not considered appropriate because they are limited to conventional steels and cannot be applied to the newer generation of microalloy materials [9]. A prior study suggests that the Arata *et al.* [7] model is the most accurate HAZ hardness calculation scheme among those available prior to 1980 [10]. Since that time, the Terasaki [8] and Yurioka [9] models have appeared in the literature. There is, however, no comparative information for these models and it is not clear where one or the another ought to be applied in practice.

Two characteristic values (A and B in Fig. 1) are used to define an Arata [7] hardening curve.

(I) The (A) characteristic point corresponds to the cooling time where the coarse-grained HAZ becomes fully martensite. To obtain the coordinates of this point the following equations were suggested [7].

(a) Conventional steels

$$H(\tau_{m100}) = 835(\mathrm{C}) + 287 \quad (1)$$

$$\log(\tau_{m100}) = 2.55\mathrm{C} + \frac{\mathrm{Mn}}{6.3} + \frac{\mathrm{Si}}{3.6} - 0.92 \quad (2)$$

(b) High-strength steels

$$H(\tau_{m100}) = 835(\mathrm{C}) + 287 \quad (3)$$

$$\log(\tau_{m100}) = 5.9\left(\mathrm{C} + \frac{\mathrm{Mn}}{19} + \frac{\mathrm{Si}}{14} + \frac{\mathrm{Ni}}{37} + \frac{\mathrm{Cr}}{19} + \frac{\mathrm{Mo}}{9.1} + \frac{\mathrm{V}}{49} + \frac{\mathrm{B}}{0.13}\right) - 1.13 \quad (4)$$

(II) The characteristic point (B) corresponding to the cooling time where no martensite in the coarse-grained HAZ exists. To obtain the coordinates of this point the following equations are suggested.

(a) Conventional steels:

$$H(\tau_{mo}) = 273\left(\mathrm{C} + \frac{\mathrm{Mn}}{13} + \frac{\mathrm{Si}}{9.7}\right) + 133 \quad (5)$$

$$\log(\tau_{mo}) = 0.37\left(\mathrm{C} - \frac{\mathrm{Mn}}{1.1} - \frac{\mathrm{Si}}{0.44}\right) + 1.02 \quad (6)$$

(b) High-strength steels

$$H(\tau_{mo}) = 500\left(\mathrm{C} - \frac{\mathrm{Mn}}{38} - \frac{\mathrm{Si}}{68} - \frac{\mathrm{Ni}}{45} + \frac{\mathrm{Cr}}{9.0} + \frac{\mathrm{Mo}}{9.9} + \frac{\mathrm{V}}{2.1} + \frac{\mathrm{B}}{0.48}\right) + 153 \quad (7)$$

$$\log(\tau_{mo}) = 0.2\left(\mathrm{C} - \frac{\mathrm{Mn}}{4.3} - \frac{\mathrm{Si}}{0.4} - \frac{\mathrm{Ni}}{0.58} + \frac{\mathrm{Cr}}{0.45} + \frac{\mathrm{Mo}}{0.49} + \frac{\mathrm{V}}{240} + \frac{\mathrm{B}}{0.0024}\right) + 1.6 \quad (8)$$

For $\tau < \tau_{m100}$

$$H(\tau_{m100}) = 835(\mathrm{C}) + 287 \quad (9)$$

For $\tau > \tau_{m100}$

$$H = \frac{b}{\log_e(\tau + a)} + N \quad (10)$$

where $N = 150$ for conventional steels and 160 for high-strength steels. The constants a and b are determined from the chemistry of the workpiece and the appropriate Equations 1 to 8.

The Terasaki [8] approach is similar to the Arata [7] method but is simplified to some extent and is, therefore less cumbersome

for $\tau > \tau_{m100}$

$$H = 812(\mathrm{C}) + 293 \quad (11)$$

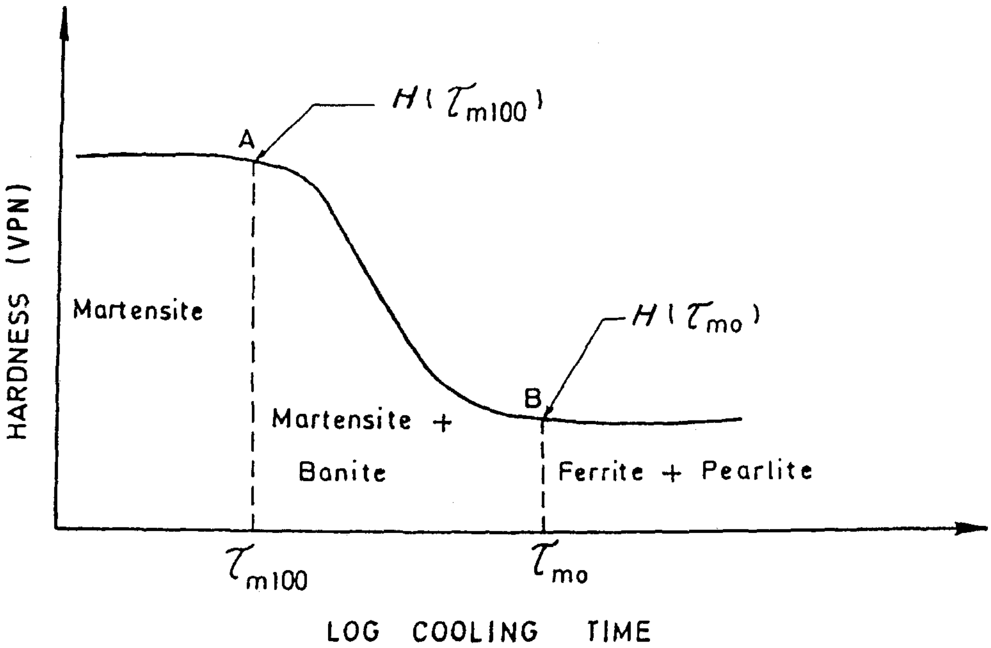


Figure 1 Schematic representation of a characteristic hardness curve [7].

for $\tau < \tau_{m100}$

$$H = [992(C) - 230(C_{eq}) + 250]\exp\left[\frac{3\tau}{310(C_{eq})}\right] + 133(C_{eq}) + 80 \quad (12)$$

and τ_{m100} is calculated according to the relationship

$$\log \tau_{m100} = 2.5\,(C_{eq}) - 1.21 \quad (13)$$

The carbon equivalent used by Terasaki [8] is given by

$$(C_{eq})_{\mathrm{Terasaki}} = C + \frac{Mn}{3} + \frac{Ni}{8} + \frac{Cr}{12} + \frac{Mo}{2} + \frac{Cu}{5} \quad (14)$$

Thus the characteristic hardening curve can be constructed knowing points (*A*) and (*B*) and using Equations 9 and 10 for the Arata [7] model while Equations (11) and (12) are needed to construct this curve according to the Terasaki model [8].

The Yurioka *et al.* [9] approach is a proposal based on yet another comprehensive study. A single relationship is used to approximate the entire characteristic hardness curve as:

$$H = 406(C) + 164(C_{eqI}) + 183 - [360(C) - 149(C_{eqI}) + 100]\tan^{-1}\left[\frac{\log\tau - 2.822(C_{eqII}) + 0.262}{0.526 - 0.195(C_{eqII})}\right] \quad (15)$$

where the carbon equivalent values are given by:

$$(C_{eqI})_{\mathrm{Yurioka}} = C + \frac{Si}{24} + \frac{Mn}{6} + \frac{Ni}{40} + \frac{Cr}{6} + \frac{Mo}{4} + \frac{Cu}{15} + \frac{(Nb + V)}{5} + 10B \quad (16)$$

$$(C_{eqII})_{\mathrm{Yurioka}} = C + \frac{Si}{30} + \frac{Mn}{5} + \frac{Ni}{20} + \frac{Cr}{4} + \frac{Mo}{6} + \frac{Cu}{5} + 10B \quad (17)$$

4. Weld-cooling models

Using only the material models described in the preceeding sections of this study enable the design and/or production engineer to construct an adequate quantitative characteristic hardening curve for steel weldments. However, it is important to present the thermal models which are commonly used to calculate approximately the 800 to 500 °C cooling time for the entire weld zone. When this time (which is a single value for a specific welding process at certain welding conditions) is applied to the characteristic hardening curve, the HAZ hardness can automatically be extracted. It is apparent that recent numerical models including finite element and finite difference [11, 14] are more accurate than conventional models especially where large central or workstation computer facilities are available. However, there is also a need for a model that can be implemented on small portable computer units even though it is recognized that there is some loss of accuracy. The conventional means of calculating the cooling time are based on the cooling rate relationships first proposed by Adams [15]. An integrated form of the Adams relationships provides the following cooling time equations

$$\tau = \left(\frac{1}{2\pi K}\frac{Q}{v}\right)\left[\left(\frac{1}{500 - T_0}\right) - \left(\frac{1}{800 - T_0}\right)\right] \quad (18)$$

for a three-dimensional heat flow (v is the welding speed) and

$$\tau = \left(\frac{1}{2\pi K C_p}\right)\left(\frac{Q}{vh}\right)^2\left[\left(\frac{1}{500 - T_0}\right)^2 - \left(\frac{1}{800 - T_0}\right)^2\right] \quad (19)$$

for a two-dimensional heat flow. It is worth noting that a relatively shallow weld is said to be three-dimensional where the heat flows away from the source both in the plane of the workpiece and in the through-thickness direction. If the workpiece is thin, heat quickly saturates the through-thickness direction and the flow is primarily parallel to the plane of the workpiece (i.e. two-dimensional). A deep penetration weld is said to be always two-dimensional regardless of the workpiece thickness [10]. The heat input rate is calculated from welding parameters using the following formula

$$Q = \eta VI \tag{20}$$

where η is the weld efficiency value which can take values of 80%, 95%, 75%, 40% and 85% for shielded metal arc weld (SMAW), submerged arc weld (SAW), gas metal arc weld (GMAW), gas tungsten arc weld (GTAW) and electron beam weld (EBW) processes, respectively. The thermal constants, K (conductivity), C_p (volumetric heat capacity), are temperature dependent for ferrous materials, but fixed values must be selected for the Adams relationships. It is generally agreed that the value of $K = 25\,\mathrm{W^{-1}m^{\circ}C^{-1}}$ and $C_p = 6 \times 10^6\,\mathrm{J\,m^{-3}\,{}^{\circ}C^{-1}}$ are appropriate for most low carbon, low alloy steels [9]. It is important to note that most welding practice is a mixture of two- and three-dimensional heat flow, thus a non-dimensional method for welding situations of this type has been proposed [16]. A thickness parameter is calculated according to the following equation [17]

$$t_r = \frac{C_p h^2 (T - T_0)}{Q/v} \tag{21}$$

where T is set to 650 °C, midway between 800 and 500 °C. The cooling time can be calculated from the following relationship

$$\tau = \left(\frac{1}{t_r}\right)\left(\frac{1}{2\pi K}\right)\left(\frac{Q}{v}\right)\left[\left(\frac{1}{500 - T_0}\right) - \left(\frac{1}{800 - T_0}\right)\right] \tag{22}$$

If t_r is less than 0.3, the two-dimensional relationship (Equation 19) should be applied. If t_r is greater than 1.25, Equation (22) degenerates to three-dimensional form (Equation 18). It is clear that Equations 18, 19, 21 and 22, together with a look-up table or curve fitting, can be easily implemented on a small computer.

It is worth noting that the transition region between two-dimensional and three-dimensional models is lacking, and more emphasis should be given to this point.

It is fair to state that the Adams [15] relationships are not the only analytical models available for calculating the cooling time. Indeed there are intermediate forms. However, it is to be emphasized that the Adams formulations represent the most basic and simple first principle relationships.

5. Experimental procedure

5.1. Materials and welding procedure

The chemical composition for the eight different steel plates used in this study is given in Table I. The steel plates from 1 to 6 were welded with SAW while the steel plates with composition numbers 7 and 8 were welded with the SMAW method. The chemical composition of the filler materials (electrodes), as well as the welding conditions used, are shown in Table II. A thermocouple is injected into the molten pool as the heat source passes and the time for the weld to cool from 800 to 500 °C is measured.

5.2. Metallographic examination

The optical metallography performed on an etched sample from each weldment of the eight metal groups, was carried out to identify the different weldment regions as well as to categorize the material microstructure of the weldment zones.

5.3. Hardness measurements

A micro-hardness survey was conducted for the eight steel weldments in order to determine the hardness

TABLE I Chemical composition (wt %) of steel plates

Steel no.	C	Mn	S	Si	Ni	Cr	Mo	Y	Al	Nb	Ti	P	Fe
1	0.12	1.27	0.01	0.21	–	–	–	–	0.02	–	–	0.01	balance
2	0.13	1.15	0.01	0.15	–	–	–	0.09	0.04	–	–	0.01	balance
3	0.12	1.12	0.01	0.21	–	–	–	–	0.02	–	0.08	0.01	balance
4	0.11	1.3	0.01	0.21	–	–	–	0.07	0.05	–	0.07	0.01	balance
5	0.10	1.17	0.01	0.24	–	–	–	0.04	0.04	0.04	0.05	0.01	balance
6	0.12	1.15	0.01	0.14	–	–	–	–	0.02	0.1	–	0.01	balance
7	0.15	0.36	0.01	0.24	2.11	1.09	0.31	0.005	–	–	–	–	balance
8	0.16	0.25	–	0.05	–	–	0.27	–	0.002	–	–	–	balance

TABLE II Chemical composition (wt %) of the filler materials and the welding conditions

Electrode no.	C	Mn	S	Si	Ni	Cr	Mo	Y	P	Cu	Fe
1	0.07/0.15	0.85/1.25	0.035	0.15/0.35	–	–	–	–	0.03	0.3	balance
2	0.1	0.6/1.25	0.03	0.8	1.4/1.8	0.15	0.35	0.05	–	–	balance
3	0.1	1.3/1.8	0.03	0.6	1.25/2.5	0.4	0.25/0.5	0.05	–	–	balance

Welding conditions for SAW and SMAW: current 525 A; voltage 28 V; welding speed 35 cm min^{-1}.

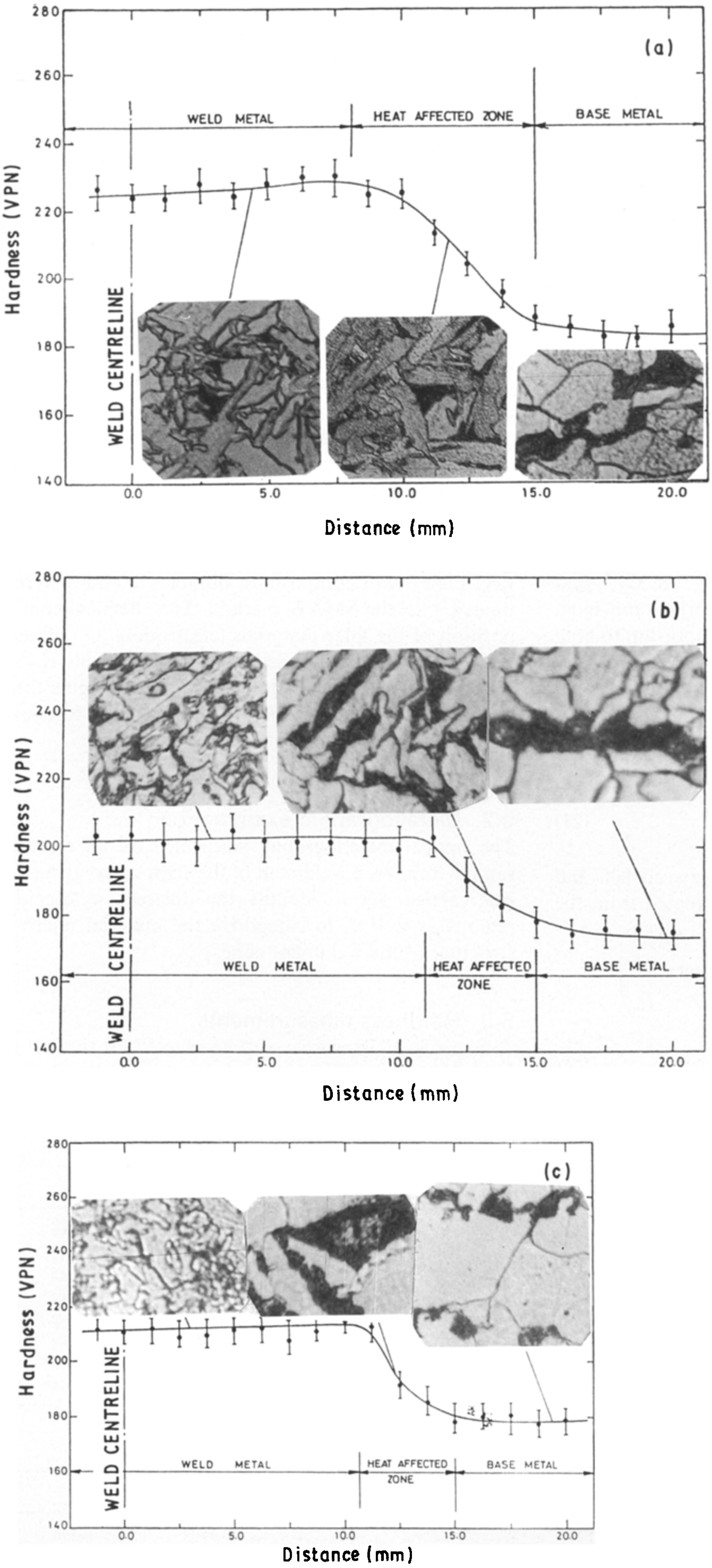


Figure 2 Hardness distribution and microstructure of different steel weldments. (a) to (f) SAW, thickness 13 mm. (g, h) SMAW, thickness 25 mm. (a) Base metal 1, filler 1; (b) base metal 2, filler 1; (c) base metal 3, filler 1; (d) base metal 4, filler 1, (e) base metal 5, filler 1; (f) base metal 6, filler 1; (g) base metal 7, filler 2 (h) base metal 8, filler 3.

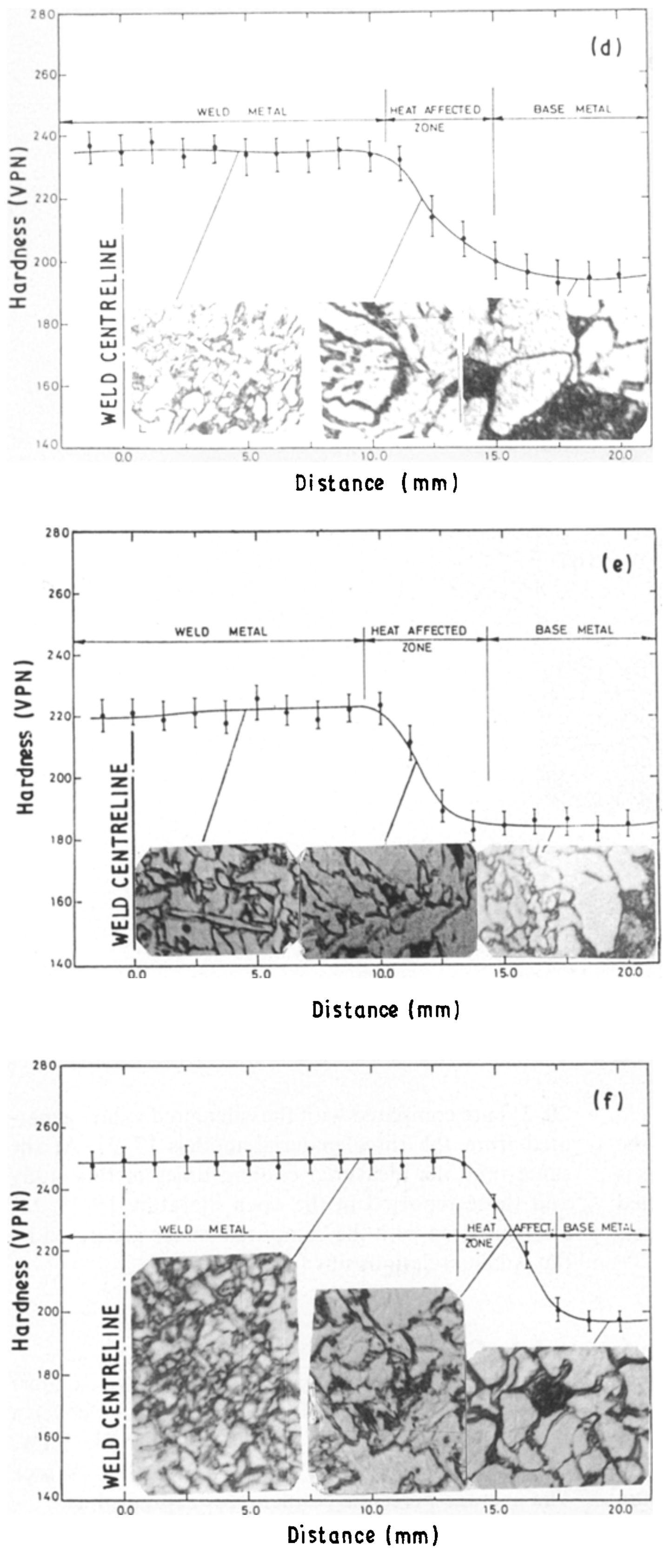


Figure 2 Continued

distribution throughout the weld zones. The microhardness profile measurements were performed using a Vickers testing machine. The specimens were polished and slightly etched with a 2% nital solution and the tests were carried out at a magnification of 400. A load of 300 gf was used and the duration of application of the load was 10 sec. The Vickers pyramid number (VPN) is calculated from the following equation [18]

$$\mathrm{VPN} = 1.8544\, P/d^2 \qquad (24)$$

where P is the applied load (kgf) and d is the average length of diagonals (mm). For each experimental point, at least ten measurements were performed and an average of the values obtained was taken.

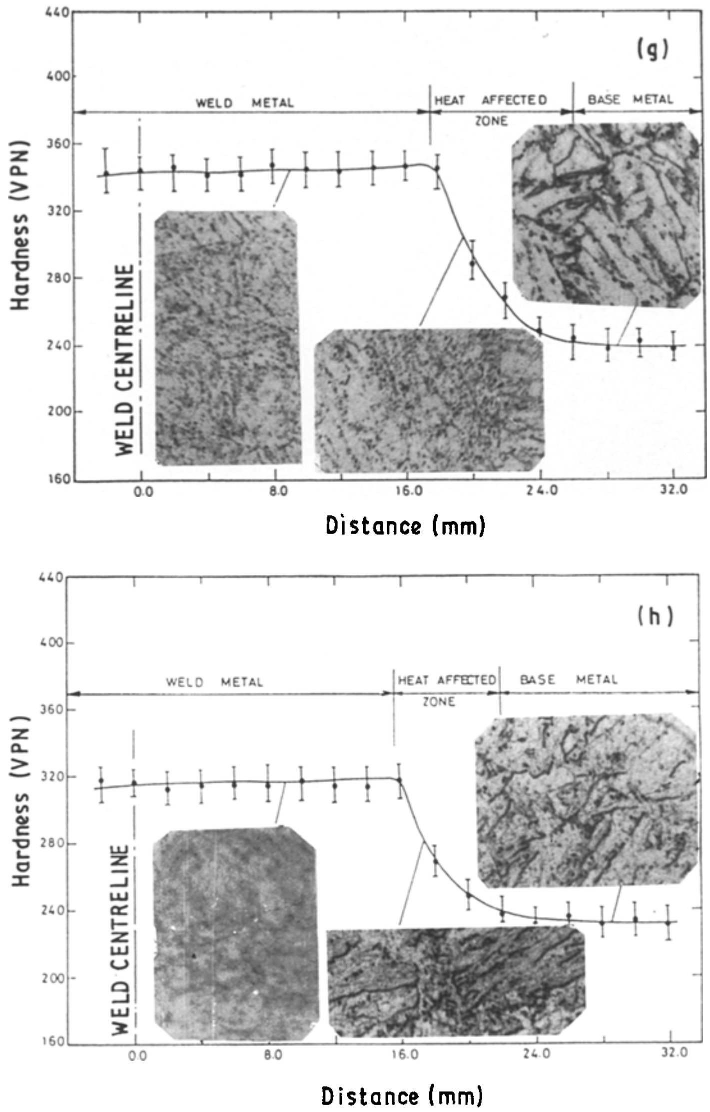


Figure 2 Continued

6. Results

Fig. 2a to h show the hardness distributions of the eight steel weldments. Also indicated in these figures is the microstructure of the base metal, heat-affected zone and the weld zone for each of the weldments under consideration.

6.1. Comparison between the calculated and measured values of both hardness and cooling time

It can be argued that one of the three materials models (Arata [7], Terasaki [8], or Yurioka [9]), and the thermal model (Adams [15]) should be implemented on small computer units for calculating HAZ hardness values. It is, however, difficult to argue further or decide which combination (material and thermal model) should be used without comparative information. There is little doubt that one model is more accurate under some conditions while another method is more accurate under other conditions. However, the philosophy adopted in this study should be the most accurate over a wide range of workpiece chemistries and welding conditions. In view of this, the HAZ hardness values measured in this study, as well as those measured by previous investigators [7, 9, 19, 20, 21] are compared with the calculated values generated from the three material models [7–9]. At the same time the measured cooling times in this study and those reported in the open literature [9, 19, 22] are compared with the computed values generated by the Adams relationships [15].

6.1.1. Cooling time comparisons

The cooling time comparisons (calculated against measured) are shown in Fig. 3. These results cover a wide range of welding processes (SMAW, SAW, GMAW and EBW) and cooling times (3 to 80 sec). The average percentage differences expressed as

$$\% \text{ difference} = \frac{(\text{calculated value} - \text{measured value}) \times 100}{\text{calculated value}}$$

are also given in this figure.

6.1.2. Hardness comparisons

The hardness comparisons are shown in Fig. 4a to c for Arata [7], Terasaki [8] and Yurioka [9], respectively. The results indicated in these figures cover a

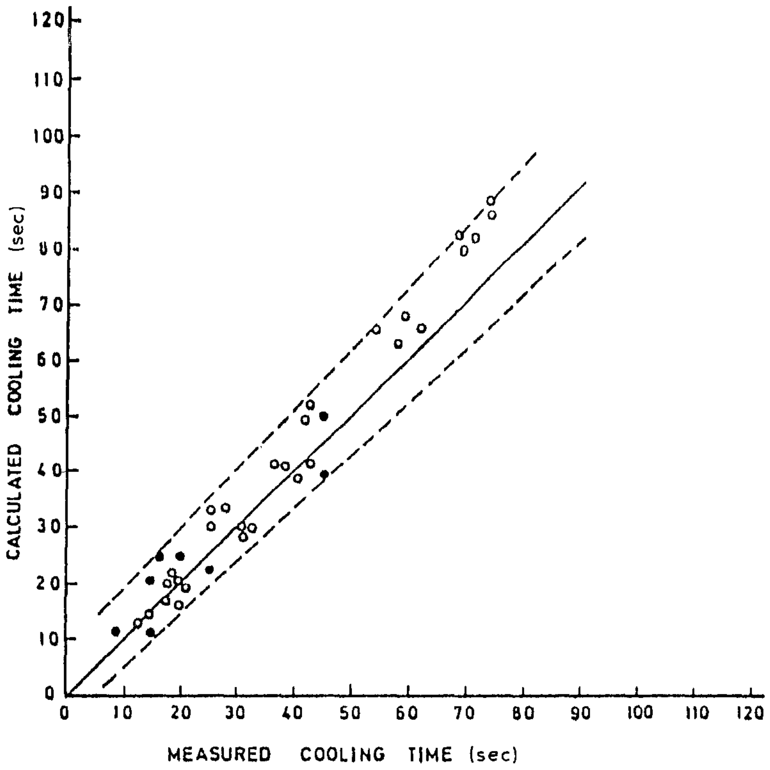
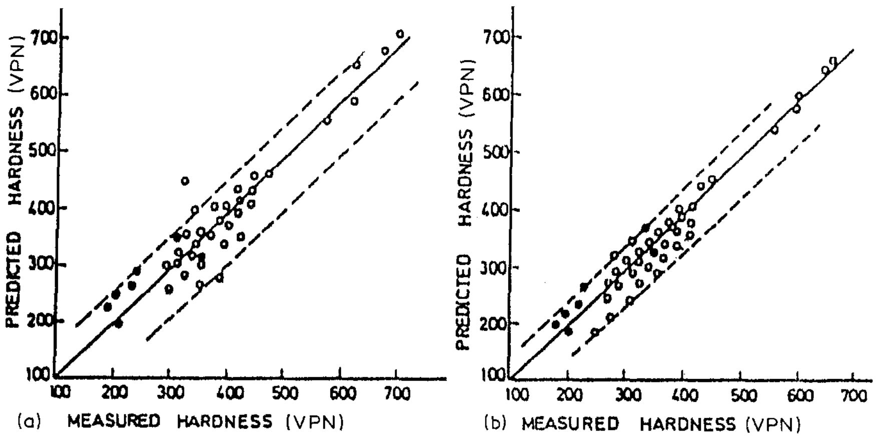
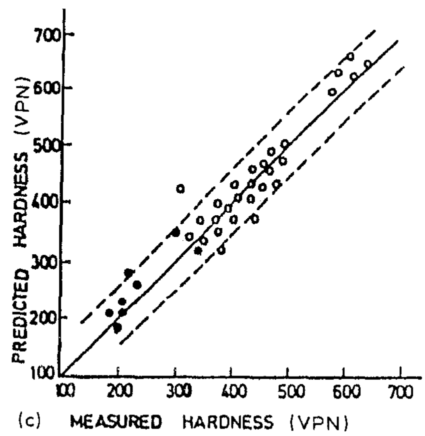


Figure 3 Calculated 800 to 500 °C weld-cooling times (using Adams relationships) plotted against measured values. The average percentage difference between the present results (●) and those of Adams [7] was 16 ± 3.5%. (○) From [7, 9, 22].





Model	Average Percentage Difference
Arata [7]	−1.6 ± 14.2
Terasaki [8]	−3.6 ± 10
Yurioka [9]	−1.9 ± 9.8

(d)

Figure 4 Maximum heat-affected zone hardness (calculated against measured) using (a) Arata's model, (b) Terasaki's model, and (c) Yurioka's model. (●) Present work, (○) from [7, 9, 19–21]. (d) Average percentage difference between calculated and measured HAZ hardness.

wide range of steels and cooling times. Carbon equivalent values calculated by the Terasaki formula ranged from 0.25 to 1.2. The average percentage difference, expressed as mentioned in the above part, is also presented in this figure. The cooling times employed in determining the predicted hardness values in Fig. 3 were calculated values.

7. Discussion

The results and analysis documented in this study clearly show that for all three models developed to estimate the hardness of the heat-affected zone of steel weldments, (Arata [7], Terasaki [8] and Yurioka [9]), the calculated HAZ hardnesses on average are quite close to the measured values. It is worth noting that the Terasaki [8] and Yurioka [9] methods are more reliable than the Arata method [7], especially in case of the steel of low carbon content (C 0.06 wt %) and welded with low heat input conditions ($\tau < 10$ sec). For plain carbon steel with high carbon content (C 0.45 wt %) and welded with high heat input conditions ($\tau > 10$ sec) the use of the Terasaki [8] and Yurioka [9] methods is recommended. In spite of the differences identified above, the similarity of the calculated HAZ hardnesses on average from the three models [7–9] is striking. All methods are useful and indeed, this study suggests that there is little to choose between the Terasaki [8] and Yurioka [9] models. Inasmuch as the models are semi-empirical, it is suggested that all three methods should be included in a computer program designed for predicting HAZ hardness. The memory required to implement each model (about 2 Kbytes RAM on an average) is not a limitation for briefcase or even some pocket calculators. In all cases hand or calculator computations are lengthy and subject to manipulation error. There is a considerable advantage in having error-free computations within a few seconds. At the same time, portable computer units and using the experience and suggestion put forward in this study offer a real convenience for busy design and production engineers.

8. Conclusions

There is little difference, on average, in the sensitivity and accuracy of the Arata [7], Terasaki [8] and Yurioka [9] models for calculating HAZ hardness levels. On the other hand, the range of application of the Terasaki [8] and Yurioka [9] methods extends to microalloy steels and they might be preferred for this reason.

Implementation of all three hardening models and the Adams [15] cooling times method required about 4 to 8 Kbytes RAM which is available on several small pocket-sized computer units.

References

1. R. D. STOUT, "Hardness as an index of the Weldability and Service Performance of Steel Weldments", Welding Research Council (WRC) Bulletin 189, 345 East 47th St, New York, NY 10017.
2. R. D. STOUT, S. S. TORR and G. E. DOAN, *Weld. J.* **24** (1945) 6255.
3. F. R. COE, "Welding Steels without Hydrogen Cracking" (The Welding Institute, Abingdon, UK, 1973).
4. M. BECKERT and R. HOLZ, *Schweiss Technik* **23** (1973) 344.
5. P. SEYFFARTH, *ibid.* **27** (1979) 58165.
6. P. BASTIEN, J. FROLLET and Ph. MAYNIER, *Metal Construct. Brit. Weld. J.* **2** (1970) 9.
7. Y. ARATA, K. NISHIGUCHI, T. OHJI and N. KOSHAI, *Trans. Jpn Weld. Res. Inst.* **8** (1979) 43.
8. T. TERASAKI, *J. Jpn Weld. Res. Inst.* **16** (1981) 145.
9. N. YURIOKA, S. OHSITA and H. TAMEHIRO, "Study on Carbon Equivalents to Assess Cold Cracking Tendency and Hardness in Steel Welding", Proceedings of The Specialist Symposium on Pipeline Welding in the 80s, Melbourne, Australia, 18 March (1981).
10. L. M. CHONG, M. J. BIBBY and J. A. GOLDAK, "Predicting Heat-Affected Zone Hardness", in the Proceedings of the Fourth International Symposium of the Japanese Welding Society-Fundamental and Practical Approaches to the Reliability of Welded Structures, Osaka, 24 November (1982) pp. 491–500.
11. G. W. KRUTZ and J. SEGERLIND, *Weld. J. Res. Suppl.* **57** (1978) 2115.
12. Z. PALEY and P. D. HIBBERT, *Weld. J. Res. Suppl.* **54** (1975) 3855.
13. E. FRIEDMAN, *J. Press. Vessel Technol. Trans. Amer. Soc. Mech. Engng.* **97** (1975) 206.
14. J. GOLDAK, A. CHAKRAVARTI and M. BIBBY, *Metall. Trans.* **15B** (1984) 299.
15. C. M. ADAMS Jr, *Weld. J.* **37** (1958) 2105.
16. E. G. SIGNES, *ibid.* **51** (1972) 4735.
17. B. A. GRAVILE, *ibid.* **52** (1973) 3775.
18. M. A. MEYERS and K. K. CHAWLA, "Mechanical Metallurgy; Principles and Applications" (Prentice-Hall, Englewood Cliffs, New Jersey, 1984).
19. F. MATSUDA and H. NAKAGAWA, *Trans. Jpn Weld. Res. Inst.* **7** (1978) 47.
20. G. M. EVANS and N. CHRISTENSEN, "Correlation of Microstructure with HAZ Embrittlement", IIW Doc., IX-823-73 (1973).
21. H. SUZUKI, *NMRI Trans.* **5** (1962) 19.
22. Th. J. VAN ADRICHEM and J. KAS, *Holectecniek* **1** (1971) 2.

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