Cracking in Restrained EB Welds in Carbon and Low Alloy Steels

Tests confirm the generality of a previous method for predicting EB weld cracking and provide new data for conditions of high restraint

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ABSTRACT. The concept of "electron beam weldability" is explored using the work of Arata et al as a basis for predicting the fusion zone hardness and susceptibility to centerline cracking (Ref. 1). The range of applicability of the approach is expanded to include low heat welds (3500 to 5500 J/cm^2) and steels with carbon equivalents up to CE = 1.0. A critical evaluation of the Arata approach is included based on these results for a series of commercial North American steels. In addition the effect of weld restraint is considered and the use of a soft shim material in the fusion zone to decrease the susceptibility to centerline cracking is evaluated.

Introduction

Probably the most troublesome defect in all welding is the cold crack. In fact, so significant is the heat-affected zone (underbead) cold crack in arc welding that the term weldability is often associated with its occurrence (Refs. 1,3). Roughly speaking the cold crack is a form of the common metallurgical quench crack (Ref. 4). When hard and brittle phases form as a result of the rapid quenching of high carbon steels, cracks will form in the presence of high tensile stress. In a weld the tensile stress arises primarily from thermal shrinkage during cooling. The fact that the cold crack occurs far more often than any other type of crack and also that it usually forms in brittle material singles it out for considerable attention when designing welds in hardenable steels.

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Fundamentally, a cold crack will form when the residual stress in the neighborhood of the weld exceeds the fracture stress of the material. The residual stress is determined by the degree of weld joint restraint and by the coefficient of expansion-stress-strain-time-temperature characteristics of the material considered over the entire thermal cycle of the weld.

At high temperatures the thermal shrinkage stress builds up until the flow stress of the material is reached and then the material flows. At lower temperatures where the flow stress of the material is high the residual stress can build up to a point where it exceeds the fracture stress, particularly in view of the triaxial state of stress encountered in the vicinity of the weld. In those cases where hydrogen is injected into the weld zone the fracture stress level changes with time and delayed fracture at low stress levels can occur. On the other hand, the material's resistance to fracture, i.e., the magnitude of the fracture stress, is determined by the chemical composition and by the microstructure encountered as a result of thermal history. The complexity of the interaction of all these parameters has so far defied reliable theoretical calculations for the cracking sensitivity of a material.

However, there have been several attempts aimed at formulating a working method of predicting the occurrence of cold cracks in the HAZ of plain carbon and low alloy steels based on empirical testing procedures such as the BWRA controlled thermal severity (CTS) test for the cruciform test. The CTS test has been recently summarized as a workable design method by Bradstreet (Ref. 7).

Essentially the cold crack is considered to be a function of the chemical composition and cooling rate in the heat-affected zone. The chemical composition reflects the tendency of the material to form hardened structures and is accounted for by the so-called carbon equivalent (CE). All other elements are expressed in terms of an equivalent amount of carbon that would cause underbead cracking. Perhaps the most common expression for CE is Bradstreet's (Ref. 7)

$$CE = C + Mn/6 + Ni/20 + Cr/10 \tag{1}$$

In general the higher the cooling rate the higher the cracking sensitivity of the material. The cooling rate in the HAZ is reflected in terms of the heat input, section size and geometry, and preheat. The principal limitation with this approach is that the state of stress is unknown and is not easily related to other joint configurations encountered in practical welding situations. However, in spite of this severe limitation the carbon equivalent method can provide useful guidance and will remain an important part of welding metallurgy until a better model is developed.

Arata et al (Ref. 1) have recently used a similar approach to establish an "electron beam weldability." While the arc welding investigations equate weldability with underbead cracking, these authors argue that the centerline crack (Fig. 1) is the predominate cold crack defect in electron beam welded hardenable steels and that it should occupy the same Important position as the underbead crack does in arc welding. Arata et al claim that butt welds having a hardness of 600 VPN or greater are subject to cracking while there is a much lower tendency toward cracking below this hardness. They then outline a method based on the carbon equivalent concept and fusion zone cooling rate for calculating the expected weld hardness and hence cracking susceptibility given the input welding parameters. Such a method is extremely useful for specifying electron beam welding parameters in hardenable steels.

It is the purpose of this paper to test the validity of the Arata method for a series of commercial North American steels where strict compositional control is not assured. The approach is further extended to include low heat input and high carbon equivalent situations. In addition, the effect of high restraint is introduced by using the cruciform weld configuration. Finally the feasibility of adding alloying elements to the fusion zone to decrease cracking sensitivity is investigated.

Arata Electron Beam Weldability

As mentioned in the introduction, Arata et al claim that electron beam butt welds having a fusion zone hardness of 600 VPN or greater are susceptible to centerline cracking (Ref. 1). They suggest that if the fusion zone hardness is predicted then so is the cracking susceptibility of the weld. They have established the following relationships for the fusion hardness of plain carbon (Eq. 2) and low alloy (Eq. 3) steels (Ref. 8):

$$H_v = \frac{1233}{\tau^{0.44}} CE + 58 \quad (2)$$

$$H_v = \frac{955}{\tau^{0.22}} CE + 157 \quad (3)$$

where

τ = cooling time between 800 and 500 C
CE = carbon equivalent

The cooling time τ can be determined from the input welding parameters by:

$$\tau = 3.8 \times 10^{-2} \left[\frac{0.8 V_b I_b}{v_b\, t}\right]^2 \left[\frac{1}{(500-T_0)^2} - \frac{1}{(800-T_0)^2}\right] \quad (4)$$

where
V_b = beam voltage (KV)
I_b = beam current (ma)
v_b = welding speed (cm/sec)
t = penetration depth (cm)
0.8 = typical efficiency for converting electron beam energy to energy absorbed in the weld
T_0 = preheat temperature (C)

The carbon equivalents CE are given by:

$$CE = C + Mn/3 + Si/45 \quad (5)$$

for plain carbon steels, and by:

$$CE = Mn/4 + Si/30 + Ni/35 + Cr/57 \quad (6)$$

for low alloy steels.

Equations (2), (3), (5) and (6) are the result of a regression analysis on a large number of experimental tests. While factors such as grain size and thermal history are known to have some effect on final hardness, the chemical composition and cooling rates are by far the most dominant factors. Therefore, only factors reflecting the cooling rate (τ) and the composition (CE) are included in Arata's approach.

Equation (4) relating the cooling time between 800 and 500 C is the result of a two-dimensional heat flow analysis of an electron beam weld (Ref. 9). The equation can be rewritten according to

$$\tau = 3.8 \times 10^{-2}(X^2) \left[\frac{1}{(500-T_0)^2} - \frac{1}{(800-T_0)^2}\right] \quad (7)$$

where $x = 0.8V_bI_b/(v_b t)$ and physically is the energy per unit through thickness area (J/cm²) along the centerline of the weld (Fig. 2).

It has recently been shown that for the two dimensional heat flow frequently found in electron beam, laser and plasma welds, X is an independent welding parameter and that X and T_0 completely describe the welding conditions (Ref. 10). To facilitate the use of equation (4), it is plotted in its modified form (Eq. 7) as shown in Fig. 3. To determine the cooling time between 800 and 500 C (τ), the quantity X is first calculated from the input welding parameters V_b, I_b, v_b and t. The value of τ is then taken from the

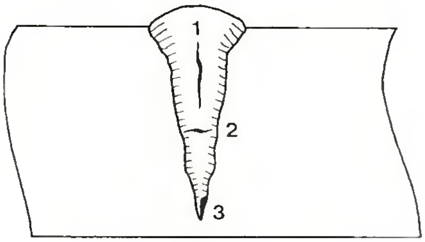

Fig. 1 — Defects that can occur in an electron beam weld fusion zone

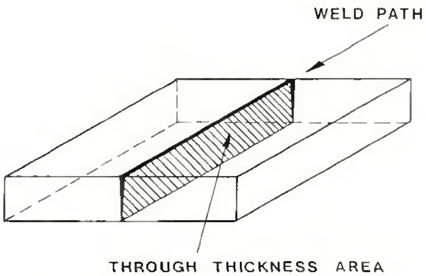

Fig. 2 — Through thickness area of an electron beam weld

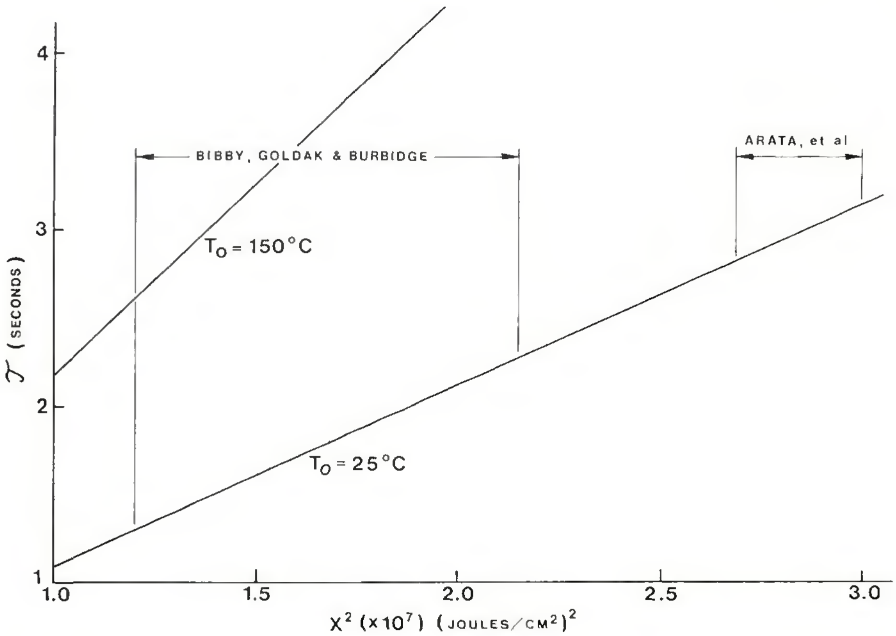

Fig. 3 — Cooling time vs input welding parameters for electron beam welds determined from the relationship shown in Eq. (7)

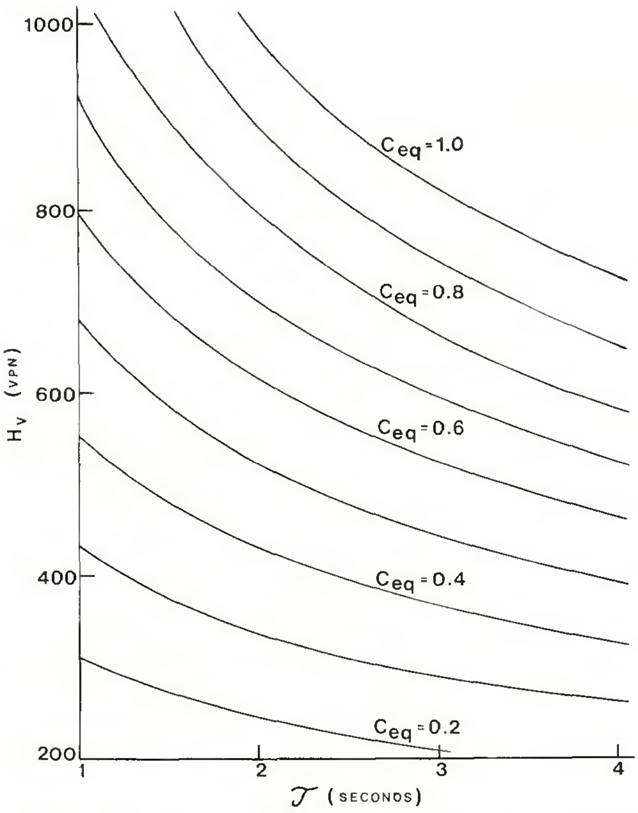

Fig. 4 — The fusion zone hardness vs the cooling time τ (between 800 C and 500 C), plain carbon steel

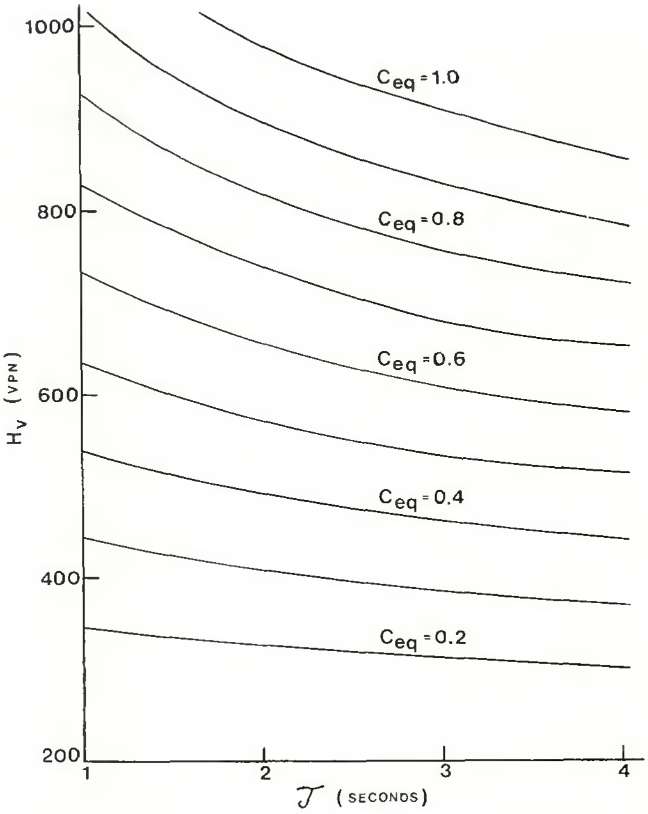

Fig. 5 — The fusion zone hardness vs the cooling time τ (between 800 C and 500 C), low alloy steels

Table 1 — Nominal Compositions and Carbon Equivalents (CE) for Steels Used in this Investigation

Steel		C	Mn	Si	Cr	Ni	Mo	CE
AISI	1020	0.21	0.4	0.2				0.34
AISI	1025	0.25	0.4	0.2				0.38
AISI	4130	0.30	0.5		0.95		0.20	0.42
CSA	G40.8B	0.20	1.15	0.25				0.46
AISI	1035	0.35	0.74	0.2				0.60
AISI	4340	0.40	0.75		0.8	1.7	0.25	0.66
AISI	1045	0.46	0.75	0.2				0.70
AISI	1095	0.95	0.40	0.15				1.08

AISI — American Iron and Steel Institute
CSA — Canadian Standards Association

appropriate curve for the welding preheat used from Fig. 3. The cooling time τ together with a carbon equivalent calculated from equation (5) or (6) are substituted into either equation (2) or (3) and a hardness determined. Alternatively the hardness can be taken directly from Figs. 4 or 5.

As indicated from the above the Arata approach is quite simple to use and would be useful if it works. Since his method is the result of a regression analysis, it might reasonably be expected to work for his carefully controlled experimental conditions and his particular steels. The question arises "does it work for other electron beam welding conditions; e.g., low heats vs Arata's higher heat welds and for commercial steels using nominal analyses." If it is to be truly useful, it will have to pass these tests. To answer these questions a series of 3/16 in. (0.476 cm) commercial North American steels were butt welded (Table 1) with a 70 kV, 25mA, electron beam, a welding speed of 15 ipm (0.63 cm/s) and no preheat. These welding parameters correspond to X = 4666 J/cm² ($X^2 = 2.18 \times 10^7$) and a preheat T_0 = 25 C.

The focus (i.e., beam size) was adjusted so that these parameters did not quite penetrate, ensuring that no beam power was lost from the backside of the weld. The energy range used in this investigation was considerably lower than that used by Arata et al presumably because he was using a low voltage machine (30 kV) and we were using a higher voltage machine (70 kV). Hence the beam size used in the present investigation was probably smaller. The energy range for both investigations is shown in Fig. 3. The fusion zone microhardness was measured on the Vickers scale using a 300 g load. Table 2 shows the results of these tests compared to the hardness values predicted by Eqs. 1 and 4.

Our experimental results are in amazingly close agreement with the calculated results. This is, perhaps, fortuitous, in view of the large number of possible differences between the model and experiment. However, in view of the fact that agreement between the experimental and predicted hardness was found, even though the input welding parameters in our investigation were very different from Arata's and commercial steels were used, is very encouraging. Furthermore, the chemical analysis of these steels was not exact — the AISI specifications analyses were used since this would likely be the only composition available in practice.

What are the limitations of the model? The first point to note is that it is based on two dimensional heat

Table 2 — Fusion Zone Hardness and Cracking Susceptibility of Electron Beam Welded Plain Carbon and Low Alloy Steels

Steel		CE	H_V (Calc.)	H_V (Measured) ± 30	Cracks[a]
AISI	1020	0.34	357	315	—
AISI	1025	0.38	390	370	—
AISI	4130	0.42	492	410	—
CSA	G40.8B	0.46	460	390	—
AISI	1035	0.60	583	520	—
AISI	4340	0.66	682	620	—
AISI	1045	0.70	670	630	—
AISI	1095	1.08	1003	895	10%

(a) This is an estimate of the amount of centerline cracking visible on the surface of the weld vs the total length of butt weld

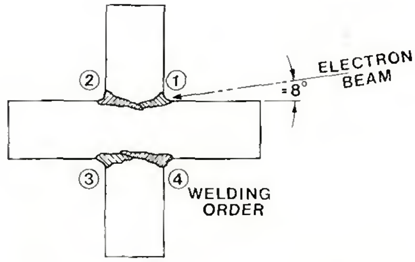

Fig. 7 — Cruciform weld sample used to test high restraint electron beam welds

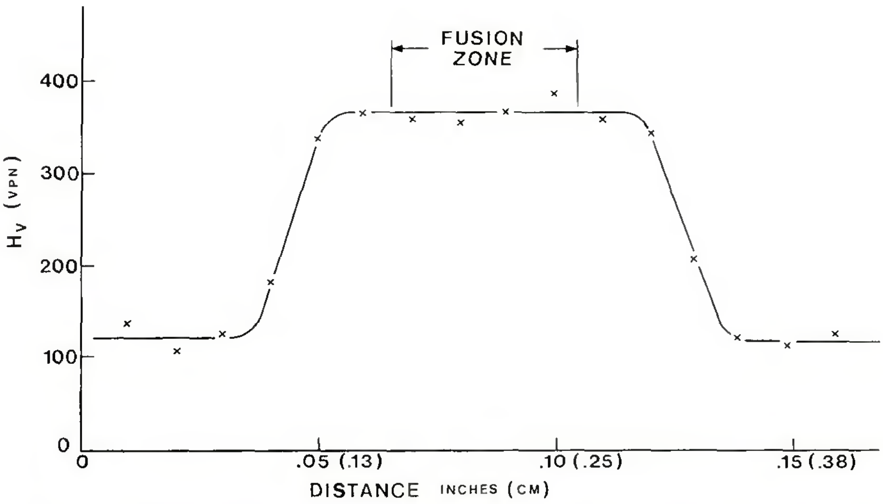

Fig. 6 — A microhardness traverse across the fusion zone of a G40.8B butt weld

flow. This requires that the fusion zone have a high depth to width ratio — of the order of 5:1 (Ref. 11). There is some argument about the validity of two dimensional heat flow in the puddle where there is extensive convective mixing. However, convective mixing is only a factor in the liquid and certainly does not occur in the solid state. Once the beam has passed a given point the heat flow from there on is two dimensional. By and large, the two dimensional model has proved very useful for a number of independent investigators (Refs. 1, 11, 12).

The second point that needs clarification is what are the valid ranges of power inputs and preheat temperatures? We have investigated heat inputs as low as X = 3507 J/cm^2 and found good agreement between the predicted and experimental hardness values. At the same time Arata's high power input of 5472 J/cm^2 suggests a power range of at least 3507 to 5472 J/cm^2. However, it is not sufficient to define input power limits without also taking into account preheat. Arata's work would suggest that the approach is valid for preheats of at least 300 C. The combination of 5472 J/cm^2 and 300 C preheat corresponds to the longest cooling time investigated — 28 seconds. The shortest cooling time, 1.5 seconds, corresponds to an input power of 3507 J/cm^2 and a room temperature preheat. We would suggest at this point that these are very nearly the limits of this approach.

The evidence for this contention is contained in the hardness values of Table 2. In several cases the hardnesses obtained are close to full hard, e.g., a hardness of 670 for SAE 1045 compared to a full hard value of ~ 700. A shorter cooling time would give predicted hardness values higher than full hardness (Eqs. 2 and 3) which of course is impossible. We would suggest that the same argument applies to very long cooling times $\tau > 28$ seconds. Arata's results indicate that the weld zone is very nearly fully soft, i.e., 300 VPN in the weld zone of a 0.50 C material compared with annealed value of 200 VPN. Clearly the material won't soften much further even though no limit is indicated in Eqs. 2 and 3.

We would, therefore, suggest that the procedure is limited to those input powers and preheats that give cooling time values ranging from 1.5 to 28 seconds. This then is the working range for these steels.

Arata has suggested some specific compositional limits but perhaps it suffices to say that the approach seems to be quite valid for plain carbon and Cr, Ni, Mo low alloy materials with a CE of less than 1.0 w/o. It was somewhat surprising to see reasonably good agreement between the predicted and experimental hardness of SAE 1095 material as the carbon (0.95 w/o) is well outside the carbon range considered in Arata's regression analysis (0.1 to 0.55 w/o C) and considerable retained austenite is expected. The hardening mechanism is, therefore, somewhat different for SAE 1095 than for the other steels. Nevertheless there is reasonable agreement and one can only conclude that the mechanism changes are slow enough as the carbon increases so that it is insignificant.

The hardness across the entire fusion zone is relatively uniform as indicated in Fig. 6. This is predicted from the heat flow model (Ref. 11). At the same time Arata used a 10 kg load while a 300 g microhardness load was used in this investigation. The difference in load did not seem to cause any discrepancy.

High Restraint Joints

Arata et al suggested that centerline cracks would probably be encountered at much lower hardness values in high restraint joints (Ref. 1). Restraint plays just such a role in arc welding and underbead cracks are far more probable in high restraint situations. To test this contention and to test the validity of Arata's approach under high restraint situations, a series of cruciform sections were welded (Fig. 7). In this case the electron beam is brought in at an angle of about 8 deg. and the weld flange is fused as indicated. The last weld (No. 4) is said to be under a very high restraint situation and is the one that is examined for cracks (Ref. 13).

Fig. 8 — (a) A cross section showing crack free cruciform welds in an SAE 1020 steel; (b) Cruciform welds in SAE 1045 material showing a large centerline crack clearly visible from the top of the weld

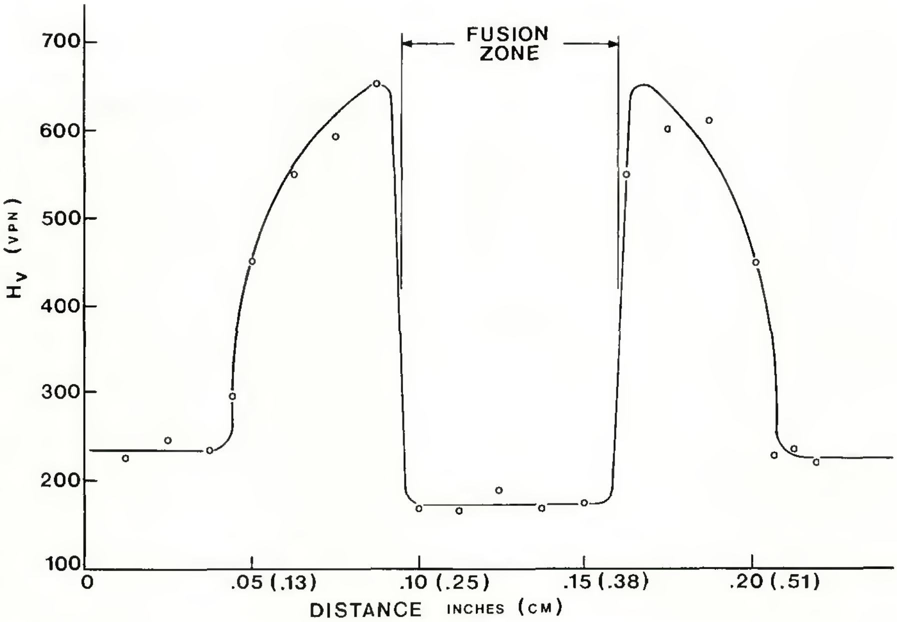

Fig. 9 — Microhardness traverse across an electron beam SAE 1045 weld with a nickel shim addition

As in the butt welding situation a 70 kV, 25 mA beam, a weld speed of 15 ipm (0.63 cm/s), and no preheat were used. The last weld hardnesses (predicted and measured) as well as the cracking susceptibilities are given in Table 3. A typical cruciform that did not crack is compared with one that did crack in Fig. 8.

Although these results are limited we would suggest that a tentative hardness limit of ~ 400 VPN should be set for high restraint joints. As in the case of the butt joints the results indicate that the Arata approach will predict the fusion zone hardness values reasonably well. This would indicate that even in the cruciform configuration there is predominately two dimensional heat flow.

Table 3 — Fusion Zone Hardness and Cracking Susceptibility of Electron Beam Welded High Restraint Joints

Steel	CE	H_V (Calc.)	H_V (Measured) ± 30	Cracking[a] %
SAE 1020	0.34	357	330	—
SAE 1025	0.38	390	350	—
AISI 4130	0.42	492	415	10
CSA G40.8B	0.46	460	405	—
SAE 1035	0.60	583	550	95
AISI 4340	0.66	682	620	95
AISI 1045	0.70	670	690	95
AISI 1095	1.08	1003	825	95

(a) A percentage of total centerline length that is clearly cracked with visual inspection

Table 4 — Fusion Zone Hardness and Cracking Susceptibility of Electron Beam Welded High Restraint Joints With Shim Additions to the Weld Zone

Material	Carbon equivalent in fusion zone[a]	H_V (Calculated)	H_V (Measured) ± 30	Cracking, %
SAE 1045	0.70	670	600	95
SAE 1045 with iron shim	0.38	390	380	50
SAE 1045 with nickel shim	—	—	170	50

(a) Calculated by dilution based on the metallography of the fusion zone

Shim Additions to the Weld Zone

In an effort to lower the hardness in the fusion zone and hence prevent cracking in high carbon equivalent material, soft iron and nickel shims were added to SAE 1045 material. A method of preventing cracking such as this is often preferable to preheating which is usually difficult and expensive. This has been suggested on a number of occasions (Refs. 14, 15). Three identical tests were run for the series of steels contained in Table 1 — a 3/16 in. (0.476 cm) cruciform without shims, a cruciform with a 0.030 in. (0.076 cm) SAE 1006 (0.06 C, 0.40 Mn 0.21 Si) shim and a cruciform with a 0.030 in. (0.076 cm) pure nickel shim. Once again a 70 kV, 25 mA beam was used at a welding speed of 15 ipm (0.63 cm/s) and without preheat. The results are shown in Table 4.

The results of this exercise were somewhat disappointing. As expected the hardness in the fusion zone decreased. However, there was still severe centerline cracking encountered. The reason for this probably resides in the hardness and hence high tensile properties of the heat-affected zone. A hardness traverse of a welded SAE 1045 with nickel shim is shown in Fig. 9. As indicated the heat-affected zones show a hardness of ~ 650 VPN and hence a high tensile strength

Fig. 10 — SAE 1045 cruciform welds with iron shim additions. Note the misalignment and cracks in the weld zone

(~ 300,000 psi). On the other hand a fusion zone hardness of ~ 170 VPN has a low tensile strength. This means that almost all of the thermal shrinkage is taken up in the soft fusion zone. It is our contention that the thermal stress in this region is above the true stress at fracture and the material tears. At the same time, to obtain sufficient dilution, a fairly large shim is required and aligning the electron beam is difficult. An off-aligned specimen is shown in Fig. 10. The overall effect is that the usefulness of shim additions to prevent cracking is marginal in high restraint situations.

Conclusions

1. Based on the results of this investigation the authors highly recommend the use of Arata's approach for predicting the fusion zone hardness and cracking susceptibility of electron beam welds. In this investigation it worked well for a wide range of welding conditions and for commercial North American steels using nominal compositions. The range of cooling times — 1.5 to 28 seconds — probably represents the limit of usefulness of the method.

2. The present investigation confirms that butt welds with fusion zone hardnesses in excess of 600 are susceptible to centerline cracking. It is also established that in high restraint circumstances weld hardnesses in excess of 400 VPN are susceptible to centerline cracking.

3. The use of thin soft shims to prevent cracking in the fusion zone of high restraint joints is found to be very limited. The hardened heat-affected zones prevent the relaxation of thermal stresses in the fusion zone and cause tearing.

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Captions