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Notch position in the HAZ specimen of reactor pressure vessel steel

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Abstract

Variations in the notch toughness in the heat-affected zone (HAZ) were investigated by positioning the Charpy V-notches along the line normal to the weld fusion line of a SA 508 Cl.3 reactor pressure vessel (RPV) steel. In the notch position for common surveillance HAZ specimens, rather higher toughness values were acquired. The minimum properties were noted in the region of 4–5 mm apart from the fusion boundary, where the values of toughness and strength were both poorer than those of the other regions of the HAZ and the base metal. The causes for these variations were discussed with reference to the microstructures from the actual and the simulated welding processes. © 1998 Elsevier Science B.V. All rights reserved.

1. Introduction

Traditionally, the heat-affected zone (HAZ) adjacent to the weld fusion line has been known to give lower toughness values than the other regions since the local temperature peak from the welding process rises above 1100°C and produces the coarse-grained microstructures in this region [1–5]. This hypothesis may have forced the notches of the surveillance specimens to be positioned nearer to (less than 1 mm) the fusion line in most codes, standards, and regulatory requirements such as, ASTM E 185 in USA, RCC-M App. SI in France, KTA 3203 in German, and JEAC 4201 in Japan [6–9]. However, recent studies on this subject have shown that the toughness of the coarse-grained HAZ region is not as bad as predicted or even better than that of the base metal. Recent revision of ASTM E 185-94 exempted the item regarding the HAZ specimens from the standard practice for surveillance tests [10]. It seems to be so because most of the surveillance test data on the coarse-grained HAZs showed rather good toughness and large scatter [11–14]. Unfortunately, however, previous studies were mostly based on the single pass welding process and published data on the multi-pass HAZ regions are limited, specially for a typical RPV material ASME SA 508 Cl.3 steel [15]. This work was undertaken with the major objective of characterizing the toughness variations with notch positions in the multipass-weld HAZ in SA 508 Cl.3 RPV steel.

2. Experiments

The chemical composition of the SA 508 Cl.3 steel studied is listed in Table 1. The weld of the full thickness (220 mm) vessel steel was produced through a multipass narrow-gap submerged arc welding process. Each characteristic region in the actual HAZ was classified in Fig. 1 after calculating the temperature distribution by the welding process.

For simulating the actual HAZ conditions, double thermal cycles were applied to the test specimens using Gleeble 1500 thermal/mechanical simulator with the heat inputs of 3 kJ/mm and the cooling rate of $\Delta t_{800-500} = 23$ s, where $\Delta t_{800-500}$ means the time required for the specimen temperature to change from 800°C to

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Table 1
Chemical composition of ASME SA 508 Cl.3 steel studied

Elements	C	Si	Mn	P	S	Ni	Cr	Mo	Fe
wt.%	0.19	0.08	1.35	0.006	0.002	0.82	0.17	0.51	Bal.

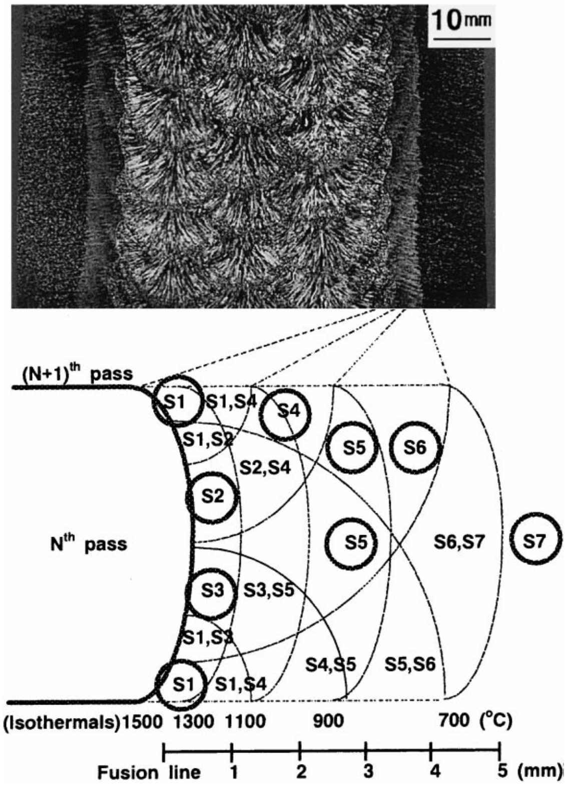

Fig. 1. Macrostructure of the actual weld HAZ and typical HAZ regions indicating simulation conditions.

500°C [16,17]. Table 2 lists the thermal cycle conditions for the simulated HAZ specimens along with the identification codes corresponding to the actual HAZ shown in Fig. 1. All the specimens were subjected to the simulated post weld heat treatment (PWHT) at 620°C for 7 h.

Charpy impact tests were performed on both the actual HAZ and the simulated HAZ specimens at −50°C. This temperature represents the lower transition regime of the base metal and is expected to show distinct differences between HAZ conditions. Tensile strength and hardness values were measured using the automated ball indentation technique on the Charpy specimens at room temperature [18].

3. Results and discussion

The width of the HAZ in the actual weld of SA 508 Cl.3 steel is found to be about 4.5 mm by macro etching shown in Fig. 1. Charpy impact tests were performed on the specimens in which the notches were positioned with a 1-mm interval from the fusion line. The test results in Fig. 2 showed a marked variation in toughness with the specimen locations in the actual HAZ. The notch toughness in the region of about 5 mm apart from the fusion line showed minimum values, while it was relatively high in the region nearer to the fusion line. However, it should be noted that the measured toughness values showed a big scatter. This is a common observation in the typical HAZ specimens and may come from the fact that the microstructural state in the HAZ is not only dependent on the distance from the fusion line but on the spatial location along the fusion line direction in multipass welding processes. Thus, the toughness variations of both directions are analyzed using the specimens of the simulated microstructures,

Table 2
Thermal cycle simulation conditions for various HAZ positions

Position [a]	Typical HAZ Region [b]	*N*th pass			Interpass Temp. (°C)	(*N* + 1)th pass		
		Heating rate (°C/s)	Holding temp. (°C/s), time (s)	Cooling rate (°C/s$_c$), $t_{8/5}$ (s)[c]		Heating rate (°C/s)	Holding temp. (°C), time (s)	Cooling rate (°C/s), $t_{8/5}$ (s)[c]
S1	U CG	256	1350, 10	13, 23	200	256	1350, 10	13,23
S2	SCR CG	256	1350, 10	13, 23	200	100	900, 10	12,25
S3	IR CG	256	1350, 10	13,23	200	56	700, 10	8, –
S4	SCR FG	100	900, 10	12,25	200	100	900, 10	12, 25
S5	IR FG	100	900, 10	12,25	200	56	700,10	8, –
S6	IR	56	700, 10	8, –	200	56	700, 10	8, –
S7	SR	45	650, 10	7, –	200	45	650, 10	7, –

[a] Refer to Fig. 1.

[b] U CG – unaltered coarse-grained, SCR CG – supercritically reheated coarse-grained, IR CG – intercritically reheated coarse-grained, SCR FG – supercritically reheated fine-grained, IR FG - intercritically reheated fine-grained, IR – intercritically reheated, SR – subcritically reheated.

[c] $t_{8/5}$: cooling time between 800°C and 500°C.

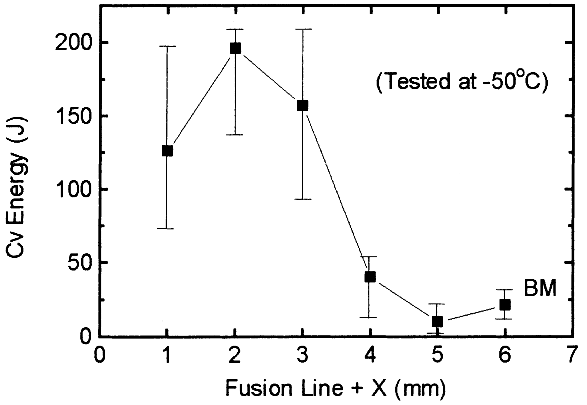

Fig. 2. Charpy V-notch test results for actual weld HAZ.

which are representatives of each spatial segment in Fig. 1.

Fig. 3 shows the variations in notch toughness of the simulated specimens with the equivalent positions in the actual HAZ. Notations S1, S2, and S3 indicate the coarse-grained HAZs, which are unaltered, supercritically reheated and intercritically reheated regions, respectively. All these coarse-grained regions showed relatively high toughness. Although most codes, standards and specifications of the surveillance HAZ tests for RPV steel specify this region as a notch position, it does not seem to be conservative from the test results in this study. S4 and S5 indicate supercritically reheated and intercritically reheated fine-grained zones, respectively. These fine-grained regions showed the highest toughness values at a distance of 2–3 mm from the actual fusion line. Significant reductions in the notch toughness were found at the regions S6 and S7 which are about 4–5 mm apart from the fusion line and indicate intercritically reheated and subcritically reheated HAZ, respectively. In these regions, the measured toughness values were lowest. Furthermore, strength and hardness values were also low in these regions. It seems to indicate a kind of softening phenomenon that has happened at around A_1 transformation temperature which is estimated about 683°C in SA 508 Cl.3 steel [19]. In other words, overtempering was supposed to have occurred by repeated thermal cycles between 650°C and 700°C [20].

The optical microstructures of the several HAZ regions are presented in Fig. 4. In the coarse-grained regions, tempered martensitic structure prevailed in the matrix with some isolated tempered lower bainite. During reheating the martensitic structure of the coarse-grained HAZ, which was developed from coarse prior austenite grains and contained martensitic packets and laths, to the three different regions (unaltered, supercritically reheated, intercritically reheated) in the coarse-grained HAZ, respectively, the fraction of lower bainite increased. Since temperature and time conditions were not sufficient for martensite transformation in the supercritically and intercritically reheated coarse-grained HAZ, unstable lower-bainite-mixed-type martensite was formed during welding process and would be tempered during PWHT. In these regions, the degree of transformation (or refinement) would be dependent on the peak temperature and dwell time.

The microstructures of supercritically reheated and intercritically reheated fine-grained HAZs exhibited very finely grained bainitic structures and showed excellent notch toughness. Owing to the rapid heating rate and short time duration at the peak temperature, the bainitic matrix in the fine-grained HAZ is partially transformed into austenite and changed to finer grained bainite during rapid cooling. It may have produced the best properties in these regions.

Intercritically and subcritically reheated regions may not have suffered such significant transformation during welding since the locations are relatively far from the fusion line. However, the test results revealed that these regions have the poorest toughness and strength. It may result from an overtempering effect due to repeated heating since the base metal already has suffered a tempering process during manufacturing. Optical microstructures for these regions showed slightly coarsened bainitic laths and carbides compared to those of the base metal. Fig. 5 shows TEM microstructural distinctions between the base metal and the reheated HAZ. Morphology and distribution of carbides, mainly cementite, can be easily distinguished in the two regions [21,22]. Based on the above observations, the softening of the matrix seems to result in the deteriorated properties in over-tempered intercritically and subcritically reheated HAZ regions.

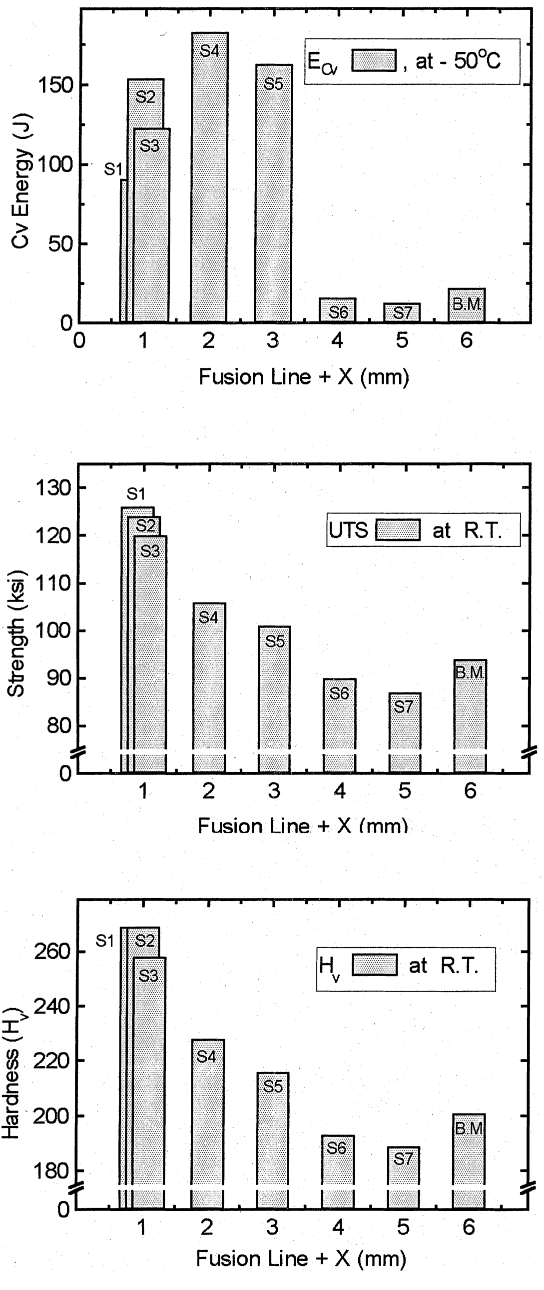

Fig. 3. Notch toughness, strength and hardness variations in various HAZ regions (S1–S7) and positions.

4. Conclusions

From detailed experimental work on the toughness variations with the locations in the multipass weld HAZ of a RPV steel, the minimum toughness values were noted at the intercritically or subcritically reheated region of 4–5 mm apart from the fusion line. It does not correspond with many codes, standards and regulatory requirements in which the specimen notches are specified to be machined within the coarse-grained region adjacent to the fusion line (less than 1 mm). The coarse-grained regions showed rather good mechanical properties. Main causes of the poor properties in the reheated regions are regarded to be the softening of the matrix due to an overtempering effect by welding heat which may be unavoidable in usual manufacturing processes. Therefore, it is proposed that the notch position in the surveillance HAZ specimen should be

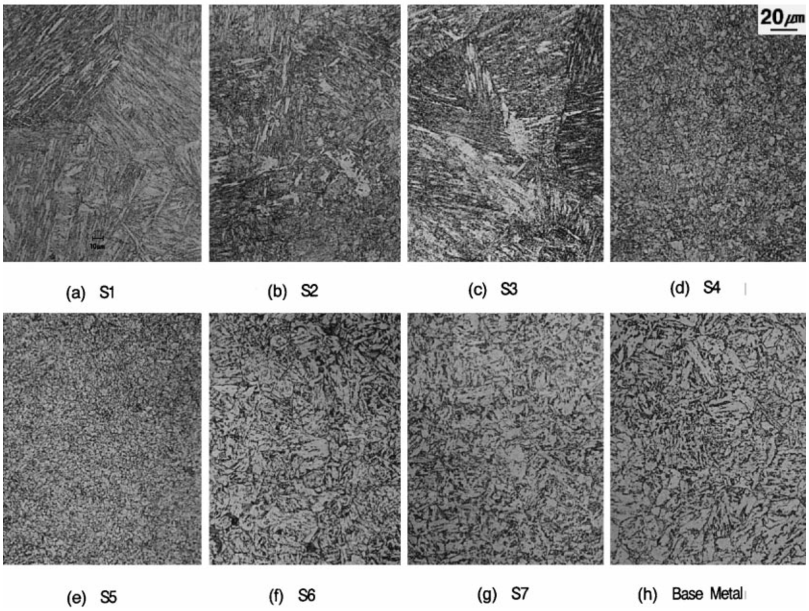

Fig. 4. Microstructures in various HAZ regions observed through OM showing CG HAZs ((a)–(c)), FG HAZs ((d) and (e)), IR HAZ (f) and SR HAZ (g). All of the HAZs were subjected to PWHT.

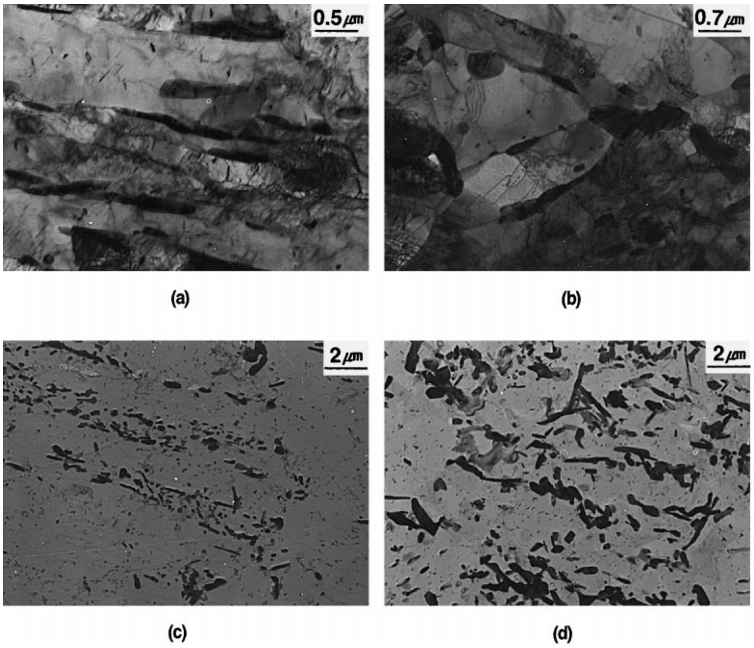

Fig. 5. Thin foil ((a) and (b)) and extraction replica ((c) and (d)) TEM microstructures of base metal ((a) and (c)) and reheated HAZ region ((b) and (d)).

placed near to the boundary between the HAZ and the base metal.

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