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Fracture behavior of heat-affected zone in low alloy steels

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Abstract

Past elastic-plastic fracture studies for leak-before-break (LBB) assessment of low alloy steel pipings have been focused mostly on the behavior of base metals and their weld metals. In contrast, the heat-affected zone (HAZ) of a welded pipe has not been studied in detail primarily because the size of the HAZ is too small to make specimens for mechanical properties measurements. In this study, microstructural analyses, microhardness tests, tensile tests and J–R tests have been conducted as a function of distance from a fusion line and temperature for HAZ materials of SA106Gr.C low alloy piping steels. For the ferrite–pearlite steels such as SA106Gr.C, the HAZ specimens showed a higher yield strength and fracture toughness compared with those of its base metal. These characteristics, despite of grain coarsening, can be explained by cleaner microstructures of HAZ materials with a finer morphology of carbides compared with pearlitic–ferritic base metals. However, the situation can be reversed for a bainitic steel since its HAZ can develop an upper bainitic structure with a reduced fracture resistance and strength, warranting further studies. © 2001 Published by Elsevier Science B.V.

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1. Introduction

The leak-before-break (LBB) approach utilizes the fracture mechanics technology to demonstrate that a high-energy fluid piping is very unlikely to experience double-ended guillotine break or their equivalent of longitudinal or diagonal splits. When the LBB characteristics is demonstrated, pipe whip restraints or jet impingement shield for the protection of pipings of safety systems and other equipment could be removed and this would result in significant savings in cost and man-Rem exposure. To this end, firstly, the measurement of material properties for the pipings must be performed for the application of LBB to piping systems [1]. Stress–strain curves and J–R curves of the piping material are required for LBB analysis. It is required that the stress–strain and the J–R curves be generated from the weakest area as the bounding characteristic of fracture resistance of the structure.

To date, LBB assessments of low alloy steel piping have been made with material properties of base metals and weld metals whereas the heat-affected zone (HAZ) of a welded pipe has not received much attention. As a result of weld thermal cycle, mechanical properties in the HAZ can be degraded by grain coarsening, the precipitation and the segregation of trace impurities. Several recent studies using simulated HAZ materials showed that the degradation of material properties is significant enough to warrant detailed investigations. [2–7]. It was reported that two distinct local zones exist in the region of weldment, which exhibit low toughness: coarse-grained HAZ (CGHAZ) [3–7] and intercritical/subcritical HAZ [2].

In the CGHAZ, it was shown that degradation of material properties is mainly caused by the increased

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Table 1
Chemical compositions of SA106 Gr.C base and weld metals (wt%)

	C	Mn	P	S	Si	Ni	Cr	Mo	V	Cu
Base	0.26	1.07	0.011	0.009	0.25	0.08	0.15	0.11	0.16	0.006
Weld	0.073	1.43	0.016	0.016	0.83	0.03	0.02	–	0.007	0.29

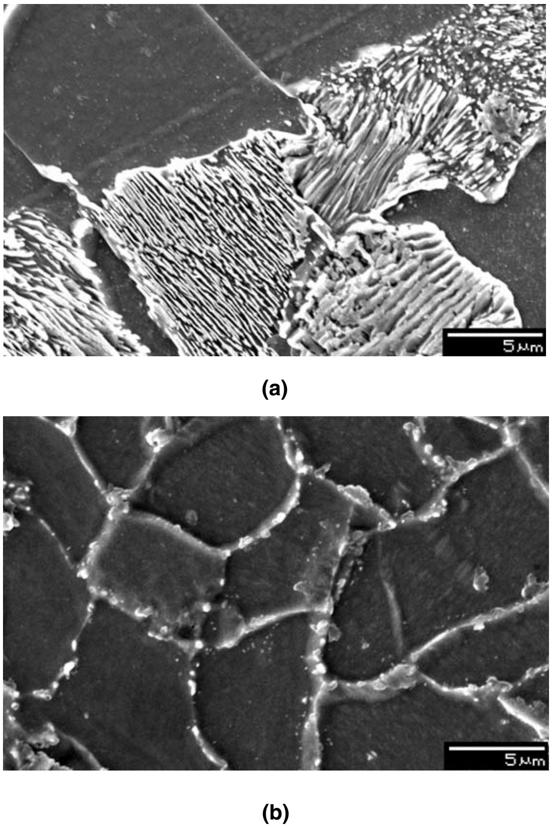

Fig. 1. Microstructures of weldment in SA106 Gr.C piping steel: (a) base metal; (b) weld metal.

grain size of prior austenite [3–6] and by the introduction of unfavorable metallurgical substructures such as untempered martensitic structures formed during rapid cooling in weld cycles [7]. In the region of intercritical/subcritical HAZ, it was shown that both mechanical strengths and impact toughness in this region can be reduced below those of either base or weld metals by the formation of upper bainite [2]. Interestingly, this was mainly caused by spherodization of carbides and subsequent softening of metal matrices by overtempering during the post-weld heat treatment (PWHT) process used to relieve residual stresses after welding of bainitic steels used as pressure vessel steels.

In the Korean Next Generation Reactor (KNGR) development, the application of LBB was explored for the main steam line that is constructed of a hot-extruded SA106Gr.C steel pipe. In this study, mechanical properties including tensile strength, Charpy impact energy, micro-hardness and fracture toughness were investigated with the welded HAZ materials of SA106Gr.C low alloy steel that is widely used for main steam line pipings in nuclear power plants. Also, the microstructural and fracture mechanical analysis of properties variations in welded piping materials were investigated.

2. Experimental

The material used in the investigation was the SA106Gr.C pipe material received from Doo-San Heavy Industry and Construction (DHIC). For the welded specimen preparation, a gas–tungsten arc welding (GTAW) was made according to the welding procedure specification of the KNGR piping. The half-K weld groove instead of actual V groove was

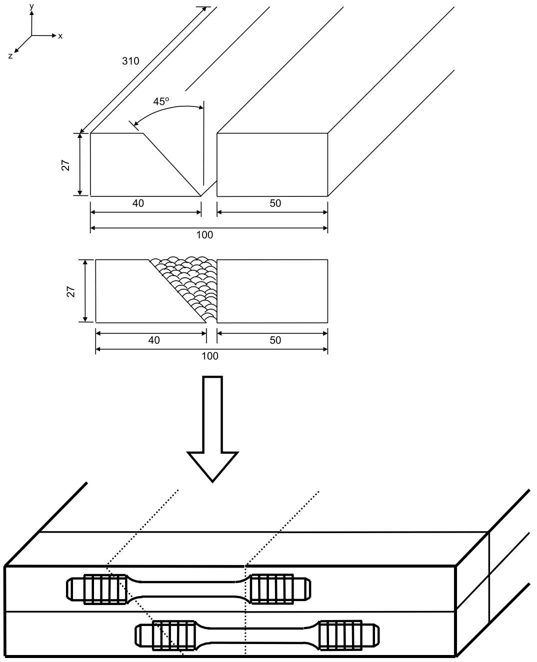

Fig. 2. Schematic of HAZ tensile specimen preparation (dimensions in mm).

used for the purpose of straight distribution of through-thickness material properties in HAZ [8]. A post-weld heat treatment (PWHT) was carried out at 610 ± 10 °C for 2 h in a box furnace in compliance with the specification. Chemical composition of base and weld materials are shown in Table 1. As shown in Fig. 1, the microstructure of base metal corresponds to a typical ferrite–pearlite structure with an average grain size of 20 μm whereas that of weld metal displays a typical ferrite structure with carbides on grain boundaries.

Tensile specimens were machined of the as-received base metal, the PWHT base metal, the PWHT HAZ, and the PWHT weld metal, respectively. Cross-weld tensile specimens were taken to locate all three different materials (weld, HAZ and base metals) within the gauge section of specimens, as shown in Fig. 2. Round bar tensile specimens with a 5 mm diameter by 25 mm gage length were tested at the relatively fast strain rate of 6.95×10^{-2}/s at room temperature, 177 and 289 °C, respectively.

Microhardness tests and Charpy V-notch impact tests were made in order to identify the potential regions of low fracture toughness. Distributions of Vickers hardness values were measured from the fusion line across the HAZ to the base metal. Similarly, Charpy impact tests were made at room temperature with specimens having different notch positions

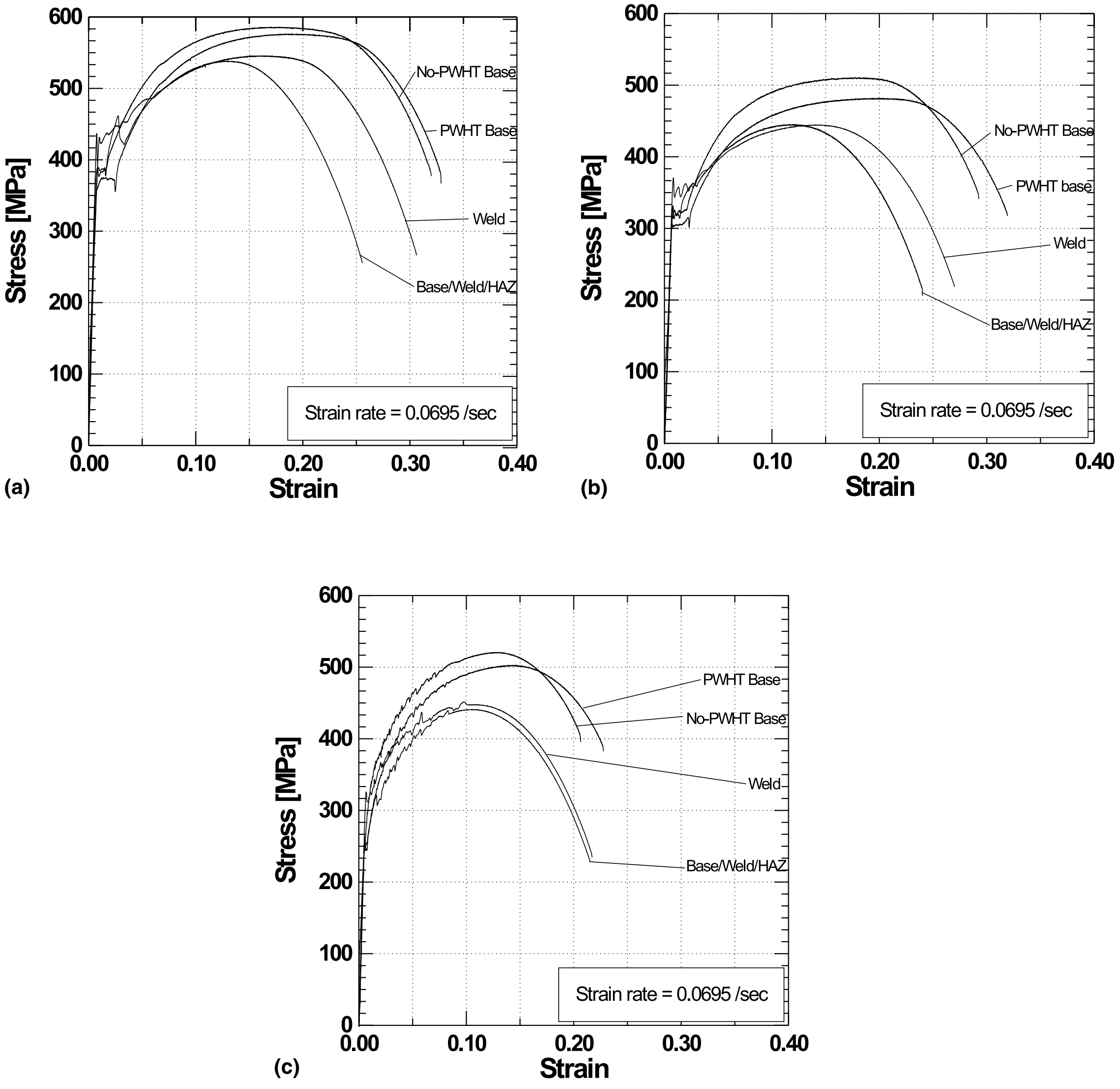

Fig. 3. Tensile test results for the both base metal and weldments of SA106Gr.C piping steels: (a) room temperature; (b) 177 °C, and (c) 289 °C.

varying from the fusion line through HAZ to base metal.

Also, J–R fracture tests were carried out using 1T CT specimens at room temperature and 289 °C for more detailed investigation of fracture behavior in HAZ region. The direct current potential drop method was employed to monitor crack initiation and to monitor crack growth. Microstructures and fracture surfaces were examined by optical and scanning electron microscopy. Samples for metallographic examination were prepared using conventional metallographic techniques.

3. Results

Fig. 3 shows the results of tensile tests conducted at a constant strain rate of 6.95×10^{-2}/s at room temperature, 177 and 289 °C, respectively. Weld metals show the higher strength but the lower ultimate tensile strength when compared with those of base metals, at all temperatures. In the tensile tests with cross-weld (weld-HAZ-base) specimens, necking and final rupture were occurred in the region of weld metal at all temperatures. Cross-weld specimen showed lower elongation than base and/or weld metal. Also, the cross-weld specimens showed secondary yield point behavior in their tensile curve, as will be discussed in the following section. From the result of micro-hardness test, Fig. 4, weld metal showed higher Vickers hardness value than base metal. This is consistent with a higher yield strength of a weld metal compared with its base metal, as shown in Fig. 3. In the region of HAZ, the maximum hardness was observed in the region next to fusion line.

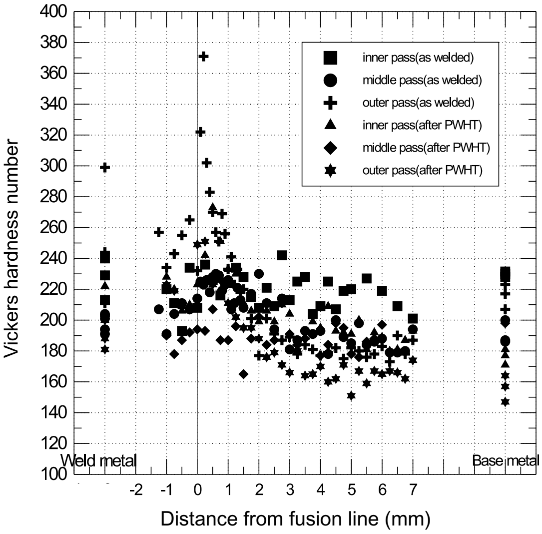

Fig. 4. Distribution of Vickers hardness in the weldment of SA106Gr.C piping steel.

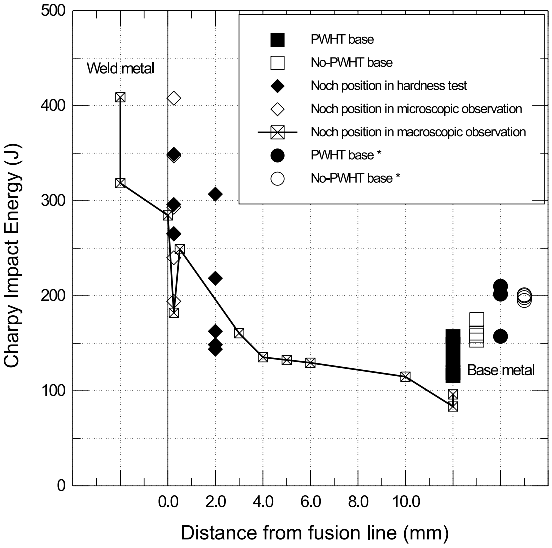

Fig. 5. Distribution of Charpy impact energy for the weldment of SA106Gr.C piping steel at room temperature.

In Charpy V-notch test results at room temperature although the region at a distance of 2 mm from the fusion line showed isolated evidence of degradation of material properties, there was no region with significantly inferior properties, as shown in Fig. 5. From Fig. 5, it can be seen that the tests were focused on specimens with the notch position at HAZ region with the highest and the lowest Vickers hardness values, and the variation of measured data was relatively large at all locations. When judged from Charpy impact test results, the narrow region at a distance of 2 mm from the fusion line indicated some degradation of material properties. However, Charpy impact energy at the location is not lower than that of its base metal. In general, there was no region with significantly deteriorated material properties in the HAZ.

Fig. 6 shows the results of J–R tests with as-received base metal, PWHT base metal, HAZ near the fusion line (CGHAZ), HAZ at a distance of 2 mm from the fusion line (ICHAZ) and HAZ at a distance of 5 mm from the fusion line (SCHAZ). From the results of J–R tests, all HAZ materials show better fracture characteristics than that of base metal. It can be seen that the test results with HAZ materials show significant scattering that was caused by the crack growth through regions with non-homogeneous material properties with complex microstructures. These non-homogeneous regions were produced by the overlapping of different weld thermal cycles and the corresponding weld HAZs in multi-pass welding.

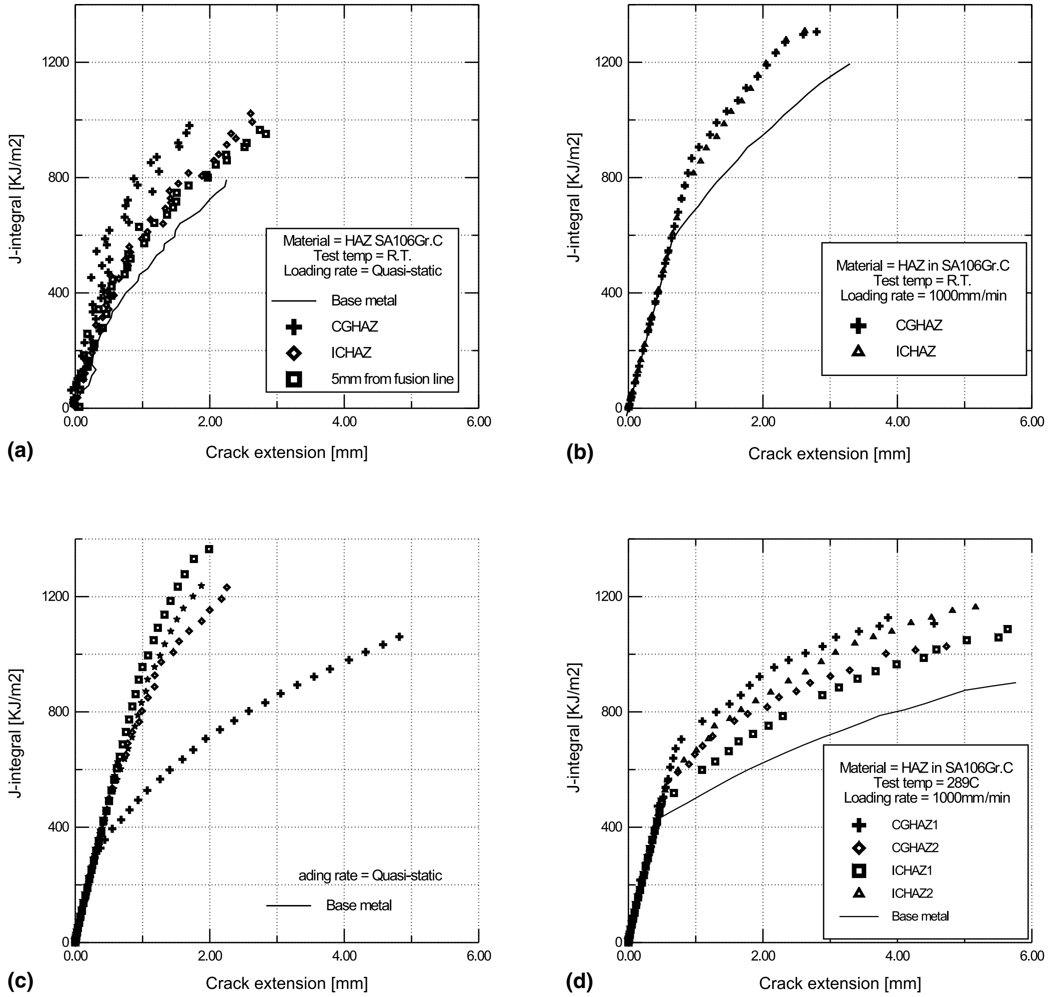

Fig. 6. Measured J–R curves in weldment for the SA106Gr.C piping steel: (a) room temperature, loading rate: 0.4 mm/min; (b) room temperature, loading rate: 1000 mm/min; (c) 289 °C, loading rate; 0.4 mm/min; (d) 289 °C, loading rate: 1000 mm/min.

4. Discussion

4.1. Tensile behavior of HAZ

In the failed tensile specimens of cross-weld (weld-HAZ-base) materials, necking and final rupture were observed in the region of weld metal at all temperatures. Also, cross-weld materials showed secondary yield point behavior in measured tensile curves. The first lower yield point in cross-weld specimens corresponds to the yield point of base metal, and the secondary yield point in cross-weld specimens corresponds to that of weld metal. It can be seen that cross-weld specimens show a typical tensile behavior of composite material composed of two materials with different yield strengths. The fact that necking and final rupture occurred in the region of weld metal at all temperatures suggests that the ultimate tensile strength of weld metal is lower than its HAZ as well as its base metal.

Also, cross-weld materials showed lower elongation than both base and weld metals, and this can be explained as follows. The necking was initiated in the base metal region of the cross-weld specimens at lower stress, and this region was elongated up to the secondary yield point corresponding to the weld region. Then the further elongation became localized to weld metal that has a limited work-hardening and hence the lowest ultimate tensile strength. Therefore, the final failure occurred at the neck in the weld.

The behavior can explain the low elongation of cross-weld materials as the length of weld metal, the main deformation area, is smaller than the gage length.

4.2. Fracture behavior of HAZ correlated with fractographic observation

Fracture properties of HAZ material in SA106Gr.C piping steel are shown to be better than that of base metal, as shown in the previous section. The observed fracture mechanics behavior can be discussed in relation with their microstructural characteristics.

The fracture surfaces of both CGHAZ and ICHAZ in SA106Gr.C steel are characterized by a typical process of micro-void coalescences with smaller dimple sizes and isolated regions of brittle fracture surfaces (cleavage facets). In contrast, the base metal shows significantly less amount of dimples with isolated step fracture facets, as shown in Fig. 7.

Fig. 8 shows the microstructures of each region in HAZ for SA106Gr.C material. The region of 0.5 mm from the fusion line (Fig. 8(a)) is the CGHAZ (CGHAZ) region that has large prior austenite grains in a bainitic structure with spherodized cementite. It is well established that grain coarsening can lower the fracture toughness of steel [3–6,9]. Fig. 8(b) shows an intercritically transformed HAZ (ICHAZ) region that has a mixed microstructure of ferrite and spherodized cementite. Fig. 8(c) represents a subcritically transformed HAZ (SCHAZ) region, which shows no discernible structural differences compared with those of base metal, as previously shown in Fig. 1(a).

From these microstructural investigations, the larger flat surfaces with fractured facets observed in the fractograph of base metal (Fig. 7(a)) can represent the decohesion of plate-like cementites within pearlites. In the HAZ region, finer spherodized cementite particles can lead to smaller dimples rather than plate-like separations, leading to higher fracture toughness values by overcoming the grain coarsening effect. Therefore, the latter upper bainitic microstructure is shown to possess the higher toughness than the ferrite–pearlitic base metal.

4.3. Comparison of SA106Gr.C with SA508Cl.3

This explanation of fracture behavior by microstructural characteristics may be extended to the HAZ behavior of bainitic steels such as SA508Cl.3 for reactor pressure vessels. As the bainitic base metal contains fine spherodized cementite particles, its fracture resistance can be substantially higher than its CGHAZ. The expectation is supported by the comparison of J–R curves for SA106Gr.C and SA508Cl.3 [10], base metals, as shown in Fig. 9. Kim and Yoon [2] reported a degraded fracture resistance of HAZ of SA508Cl.3 compared with its base metals. The finding is consistent with the current microstructural behavior since there is no benefit of removing cementite plates in SA508Cl.3. Therefore, the observation by Kim and Yoon [2] is substantiated by the results of the present study. Some pipings of PWR reactor coolant systems are fabricated of bainitic SA508 steels. For this reason, further studies are warranted for the HAZ of bainitic low alloy steels that are used in the primary piping of PWRs.

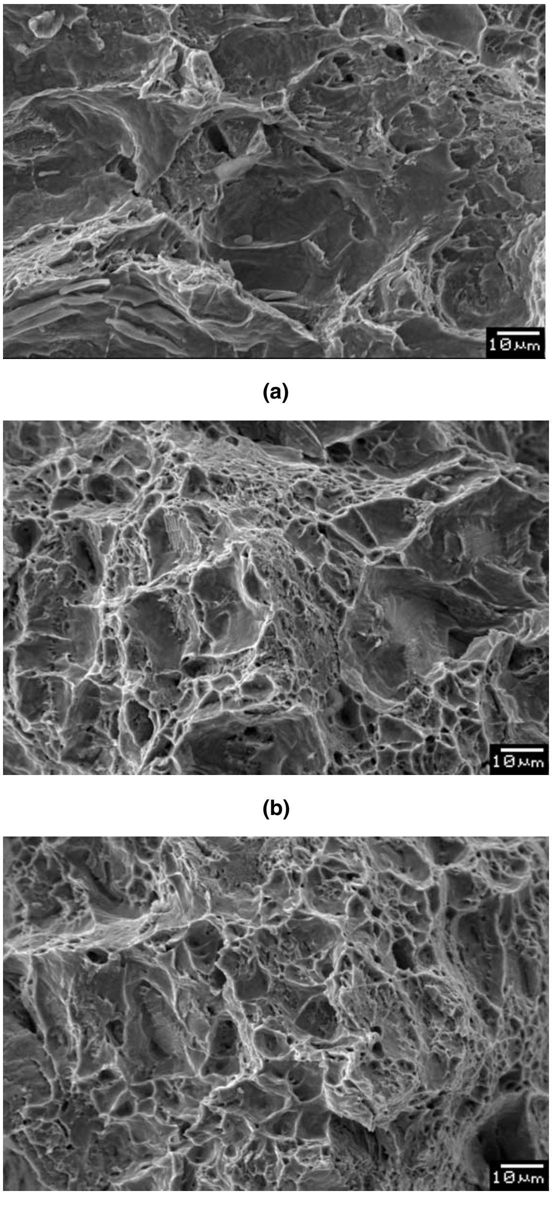

Fig. 7. SEM photographs showing fracture surfaces of the J–R specimens of SA106Gr.C piping steel tested at room temperature and 0.4 mm/min. loading rate: (a) base metal; (b) CGHAZ; (c) ICHAZ.

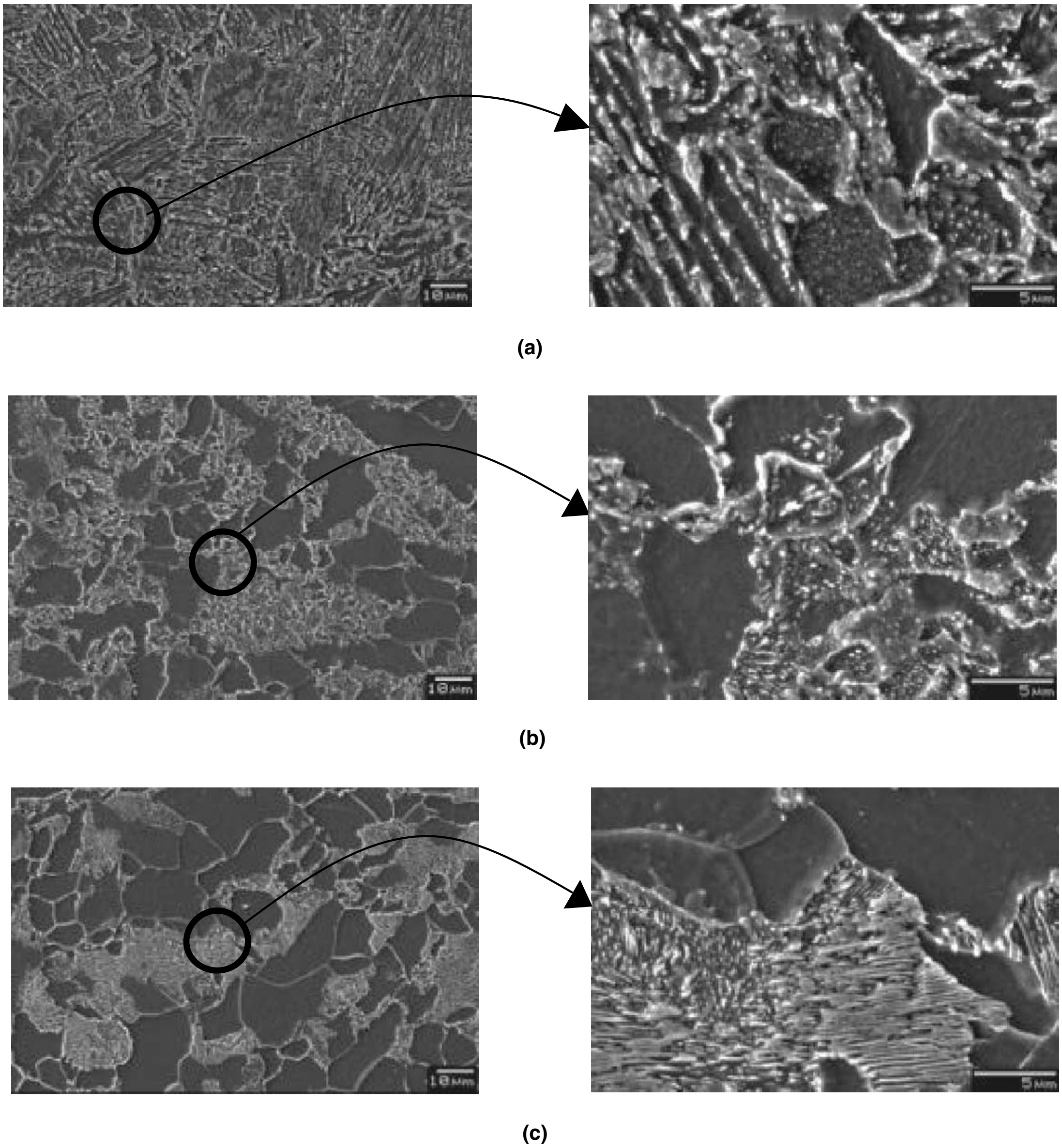

Fig. 8. SEM photographs showing microstructures of various HAZ regions in SA106 Gr.C piping steel: (a) 0.5 mm region from fusion line (CGHAZ); (b) 2 mm region from fusion line (ICHAZ); (c) 5 mm region from fusion line (SCHAZ).

5. Conclusions

From the investigation of mechanical behaviors of HAZ in SA106Gr.C low alloy steel, following conclusions are made:

1. A weld metal has a higher yield strength, but a lower ultimate tensile strength and elongation compared with its base metal and a HAZ appears to have a higher strength than the weld metal which leads to a failure of cross-weld specimen within the weld metal region.
2. For SA106Gr.C (ferrite–pearlite steel), the HAZ's showed better fracture properties than base metals at all temperatures and loading rates. This is rationalized by the fact that transformation of plate-like pearlite into finer spherodized carbide during weld thermal cycle leads to ductile dimpled rupture with significantly reduced faceted fracture. The benefit of carbide refinement overwhelms the disadvantage of grain coarsening in HAZ.
3. For SA508 (bainitic steels), such a benefit of microstructural improvement does not occur to overcome

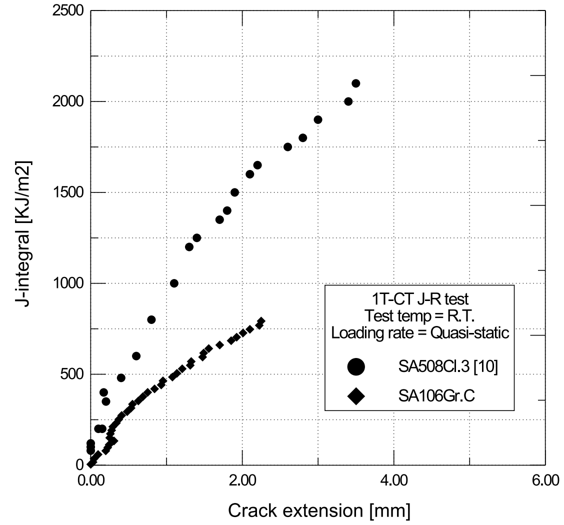

Fig. 9. Comparison of J–R curves for SA106Gr.C and SA508Cl.3 steels.

the detrimental grain coarsening in HAZ. Hence further study is warranted for the HAZ behavior of some PWR primary piping made of SA508.

Acknowledgements

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