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Weld crack assessments in API X65 pipeline: failure assessment diagrams with variations in representative mechanical properties

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Abstract

Applying accurate material properties to failure assessment diagrams (FAD) for flaw assessment has been problematic, particularly for welded joints in structures such as natural gas pipeline. In a study of API X65-graded natural gas pipeline, we evaluated material properties such as tensile properties and fracture toughness for the base metal, weld metal and heat-affected zone (HAZ), and investigated the influence on flaw assessment of variations in material properties of three regions. In particular, microtensile tests and crack-tip-opening-displacement (CTOD) tests made it possible to construct an HAZ-focused FAD reflecting HAZ properties. It was found that, when crack-like flaws exist in the HAZ, the HAZ-focused FAD yields a more accurate assessment than FADs constructed according to current codes.

Keywords: Failure assessment diagram; API X65 steel; Crack assessment; Fitness-for-service; Heat-affected zone; Natural gas pipeline

1. Background: failure assessment diagram

To satisfy the increasing demand for natural gas as a primary energy source, many natural gas pipelines have been constructed around the world; over the past 15 years Korea has constructed a number of pipelines that are 2400 km long. The gas industry is now concerned not only with constructing new pipeline but also with maintaining the old pipeline; in particular, much effort has been expended on fitness-for-service (FFS) assessment of crack-like flaws that are found in pipelines during operation.

Among the many methodologies for FFS assessment, the failure assessment diagram (FAD) is one of the most popular for evaluating crack-like flaws in in-service industrial structures [1–3]. The FADs described in various current codes such as API 579, BS 7910 and R-6 [4–6] can cover all failure modes from linear elastic fracture to plastic collapse, and thus have become the most broadly accepted methodology for assessment of natural gas pipeline containing crack-like flaws.

FADs are generally classified in current codes into three different types according to the material properties available for FFS assessment and the conservatism of the diagram; higher-level FADs require more complex data but are less conservative. Level 1 (Fig. 1a), a preliminary FAD based on the CTOD design-curve method, is the basis of the elastic–plastic fracture assessment procedure in BS 7910 [5]. Level 2 (Fig. 1b) is an alternative FAD based on the lower bound of many curves obtained from experimental data on general austenitic steel [4–6]. Both level 1 and level 2 contain universal failure assessment curves (FAC: criterion line of FAD) independent on material properties, as shown in Fig. 1. However, level 3 (Fig. 1c) is a material-specific FAD based on the reference stress model [4–6]. The FAC of level 3, defined as in Eq. (1), requires the value of reference strain, $\varepsilon_{\mathrm{ref}}$, of the target region including the flaws. Since $\varepsilon_{\mathrm{ref}}$ is defined as a corresponding true strain obtained from the tensile curve at a true stress, the tensile curve of the target region must be determined before using the FAD:

$$K_{\mathrm{r}} = \left(\frac{E\varepsilon_{\mathrm{ref}}}{L_{\mathrm{r}}\sigma_{\mathrm{Y}}} + \frac{L_{\mathrm{r}}^{3}\sigma_{\mathrm{Y}}}{2E\varepsilon_{\mathrm{ref}}} \right)^{-0.5} \tag{1}$$

Here σ_{Y} and E are the yield stress and elastic modulus, respectively; and L_{r} and K_{r} the load ratio and fracture ratio,

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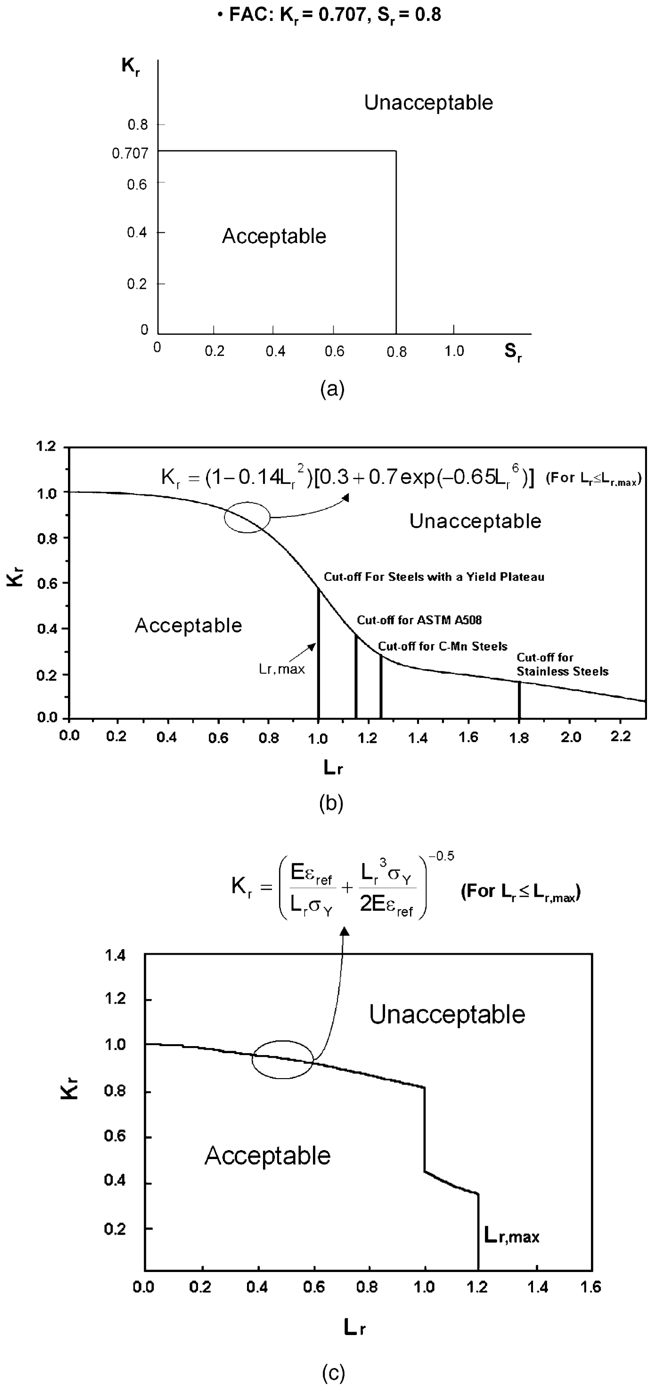

Fig. 1. Schematics of various FADs: (a) level 1, (b) level 2 and (c) level 3 FAD.

respectively, as defined in the following equations:

$$L_r = \frac{\sigma_{ref}}{\sigma_Y} \tag{2}$$

$$K_r = \frac{K_I}{K_{IC}} \tag{3}$$

where σ_{ref}, K_I and K_{IC} are applied stress, stress intensity factor, and fracture toughness, respectively. Determining the FAC and specifying a point (L_r, K_r) on the FAD to indicate a structure's present status require material properties such as yield stress and fracture toughness in Eqs. (2) and (3). Additionally, the ultimate tensile stress is also required to define $L_{r,max}$, which is a limit value of plastic collapse, as in

$$L_{r,max} = \frac{\sigma_{flow}}{\sigma_Y} = \frac{(\sigma_Y + \sigma_U)/2}{\sigma_Y} \tag{4}$$

where σ_{flow} and σ_U are flow stress and ultimate tensile stress, respectively.

Thus representative mechanical properties of the region containing a flaw must be determined in order to construct an FAD. But determining accurate material properties for FADs is a still unresolved issue, particularly with regard to weld crack assessment in welded structures such as natural gas pipelines. Generally, a gas pipeline includes two types of weldments (regions with many potential defect-producing factors [7,8]): seam welds in the longitudinal direction and girth welds around the circumference. Since the welded joints are composed of weld metal and HAZ, FAD users should evaluate the representative tensile properties and fracture toughness of the weld metal and HAZ individually. However, evaluating HAZ properties is notably difficult because of its complex microstructural gradients; in addition, the HAZ is so narrow that specimens for mechanical property measurements cannot be produced. For these reasons, current codes recommend using weld metal properties instead of HAZ properties when flaws exist in the HAZ [4–6]. For example, the use of weld metal data for flaws in regions of twice the weld metal width is recommended [3,4]. However, the HAZ often has far different mechanical properties from weld metal because of such unfavorable microstructures as coarse-grained zones arising from welding process (for examples, see [8,9]).

In particular, weldments of thermomechanical-control-processed (TMCP) steels such as the API X65 steel studied here show a greater difference between weld metal and HAZ properties than other structural steel welds because of the HAZ softening effect, due to the thermal cycle experienced in the welding process, which leads to further tempering of the already quenched and tempered region [10,11]. Therefore, in actuality, the difference in material properties between the different weld regions influences how plasticity develops at flaws and hence the relationship between the crack driving force and applied loading. These differences can produce inaccuracies in FFS assessments that can critically damage pipeline operations. With the hope of avoiding these inaccuracies, this study determined representative mechanical properties of API X65-graded pipeline (used as the main gas-transmission pipeline in Korea) individually in three regions and used these properties to construct three different FADs for each region. Crack assessment results from the FADs are also compared and discussed.

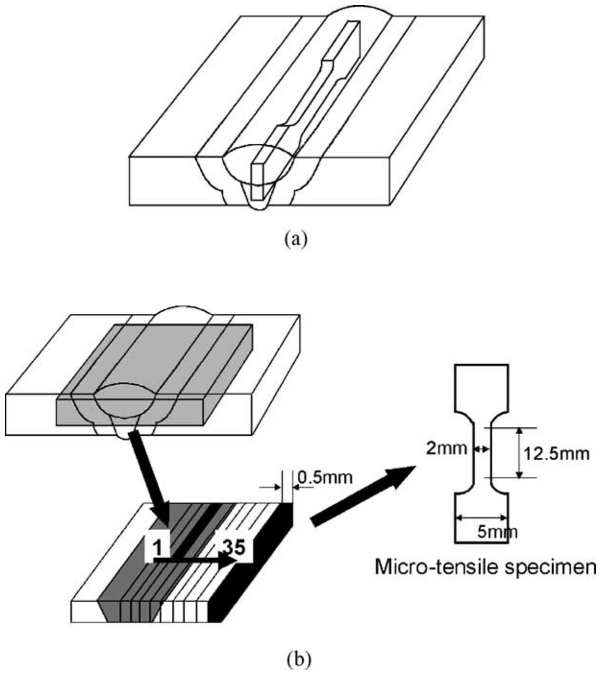

Fig. 2. Locations of tensile specimen sampling in: (a) weld metal and (b) HAZ.

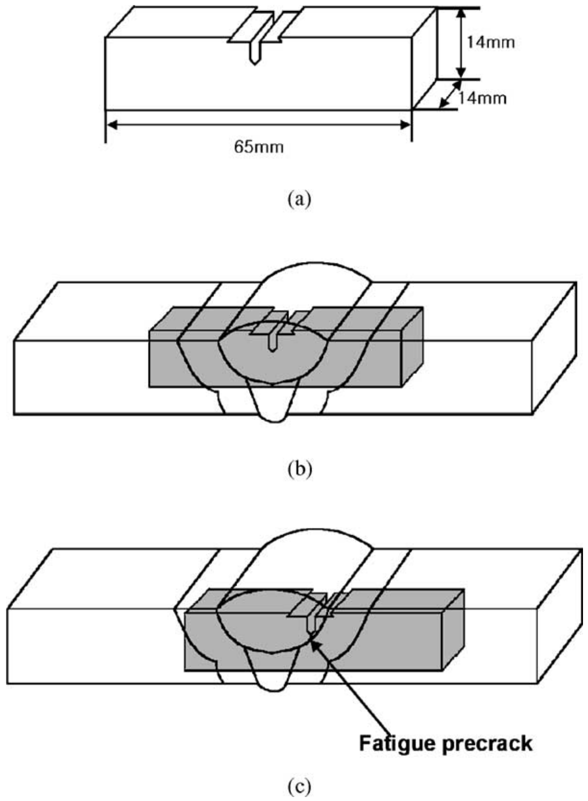

Fig. 3. Schematic diagrams of (a) CTOD specimen geometry; notch locations of (b) weld metal specimen and (c) HAZ specimen.

2. Experiments

To obtain the tensile properties and fracture toughness data needed to construct an FAD for weldments, tensile tests and crack-tip-opening-displacement (CTOD) tests were performed using specimens from the girth and seam weldments of API X65-graded natural gas pipeline of diameter 762 mm and thickness 17.5 mm. Tables 1 and 2 list the chemical composition of the base material and the welding conditions for the welds.

To obtain the tensile properties of the weldment, standard subsize specimens (gauge length 25 mm, thickness 4 mm, width 6.25 mm, as per ASTM E8 [12]) were extracted from the base metal and weld metal. In the base metal, specimens were taken from the upper, middle and lower regions in the thickness direction to assess the thickness-directional variation of properties, and similarly for specimens taken in the longitudinal circumferential directions. In the weld metal, the specimens were sampled to contain only weld metal, as shown in Fig. 2a. The HAZ, however, is too narrow to yield a standard subsize specimen. Instead, a block comprising weld metal, HAZ and base metal was extracted and sectioned in 0.5 mm thicknesses from no. 1 to no. 35, as shown in Fig. 2b. The HAZ specimens were machined into microtensile specimens of 12.5 mm gauge length, 0.5 mm thickness and 2 mm width. To verify the reliability of the

Table 1
Chemical composition of API 5L X65 pipeline steel

	Element						
	C	P	Mn	S	Si	Fe	$C_{eq.}$
Chemical composition (wt.%)	0.08	0.019	1.45	0.003	0.31	Balance	0.32

Table 2
Welding conditions for natural gas pipeline weldments

Weldment	Condition			
	Welding method	AWS	Groove shape	Heat input (kJ/cm)
Girth weldment	GTAW + SMAW	ER 70S-G, E9016-G	V	12.8–30.3
Seam weldment	GTAW + SAW	ER 70S-G, F8A4-EA3-A4	X	10.8–19.9

microtensile tests, micro-Vickers hardness tests with load 0.5 kgf were also conducted along the distance from fusion line at 1 mm intervals.

To obtain fracture toughness data for the weldment, CTOD tests were conducted according to ASTM E1290 [13] instead of a K_{IC} test (K_{IC} cannot be evaluated directly due to the size requirement). Fracture toughness was also estimated in each region. In both base metal and weld metal, surface-cracked single-edge-notched bend (SENB) specimens were extracted from the upper, middle and lower regions in the thickness direction. Fig. 3a shows the size and geometry of the CTOD specimens used. While weld metal specimens were sampled as shown in Fig. 3b, the notch tip of the HAZ specimen is near the fusion line, as shown in Fig. 3c. The fatigue precrack of HAZ specimens was located at the fusion line to evaluate the fracture toughness of the coarse-grained heat-affected zone (CGHAZ), known to be the weakest region within the HAZ [8]. Using the SENB specimens, at least five toughness values were obtained from CTOD tests under each condition, and only the minimum value was used to estimate the lower-bound toughness. The CTOD data obtained were converted into K_{IC} data for use in the FAD.

3. Results and discussion

3.1. Representative tensile properties for evaluating resistance to plastic collapse

Table 3 lists the results of tensile tests for base metal, weld metal and HAZ. In the base metal, the yield strength and tensile strength of the upper and lower regions were higher than those of the middle region. The tensile properties of the upper and lower region were within 5% of each other. These results indicate that strain-hardening effect is greater in the upper and lower regions than in the middle region. Since natural gas pipeline is manufactured by TMCP, the surface experiences greater strain hardening than the inner body during rolling [7,8]. Table 4 lists the strain-hardening coefficients of the base metal. Since generally the more material is strained, the lower the strain-hardening coefficient, Table 4 shows that the upper and lower regions experience

Table 3
Tensile properties of natural gas pipeline

Region	Yield strength (MPa)	Tensile strength (MPa)	Elastic modulus (GPa)
Base metal (seam)			
Longitudinal (upper)	497	617	209
Longitudinal (middle)	435	598	209
Longitudinal (lower)	505	625	209
Base metal (girth)			
Circumferential (upper)	488	631	210
Circumferential (middle)	453	601	210
Circumferential (lower)	499	625	210
Girth weld metal	530	678	212
Seam weld metal	568	681	212
HAZ (girth)	423	550	210
HAZ (seam)	396	567	210

Table 4
Strain-hardening coefficient of base metal

Region	Location	n
Base metal of girth weldment	Upper	0.15
	Middle	0.18
	Lower	0.15
Base metal of seam weldment	Upper	0.16
	Middle	0.19
	Lower	0.15

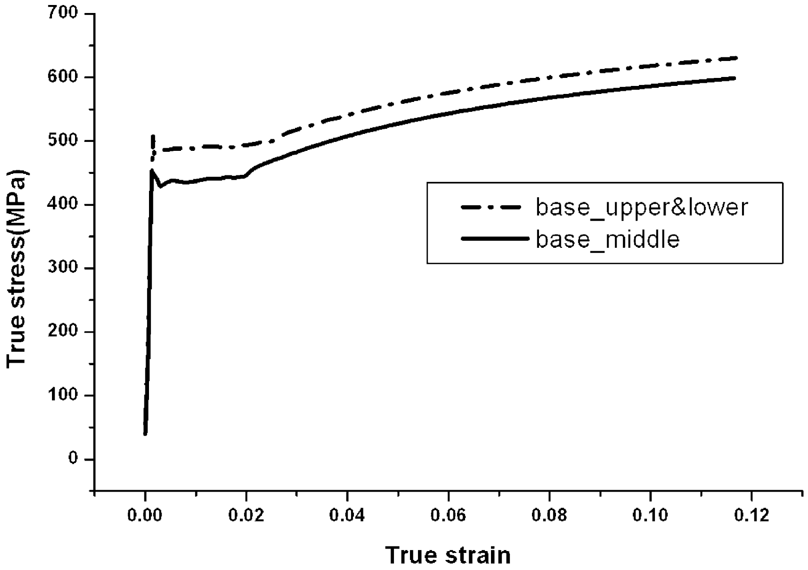

Fig. 4. Representative tensile curves for base metal.

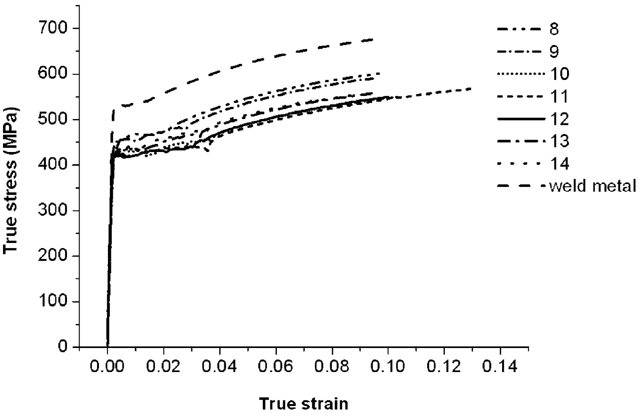

Fig. 5. Tensile curves for weld metal and HAZ.

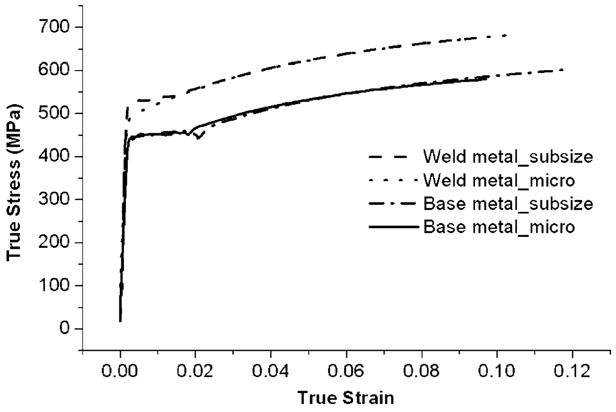

Fig. 6. Comparison between microtensile data and subsize tensile data.

higher strain hardening than the middle region. In addition, no difference was observed in the base metal tensile properties between the longitudinal and circumferential directions. The above results were used to determine the representative base metal tensile curves in Fig. 4.

In the weld metal, the yield strength and tensile strength of the seam weldment were higher than those of the girth weldment, and both weldments had higher strength than the base metal. Weldments of natural gas pipeline are overmatched for strength for in-service safety [7], and thus the tensile properties of weld metal shown in Table 3 should be applied to assess FFS using FAD when a crack is present in the weld metal.

Careful attention was given to obtaining accurate HAZ properties. Ex situ examination of sample location and data revealed that microtensile specimens from no. 8 to no. 14 in Fig. 2b represent the HAZ. Fig. 5 shows their tensile curves for the girth weldment. To confirm the reliability of microtensile data, the microtensile test results were compared with those of standard subsize tensile tests using specimens satisfying ASTM E8 [12] size requirements (since subsize tensile data could not be obtained in the HAZ), as shown in Fig. 6. The tensile curves for subsize tensile specimen and microtensile specimen show good agreement, confirming that HAZ tensile curves obtained from microtensile tests can be used to construct FADs. Fig. 7 shows the variation of ultimate tensile strength in the upper region of the HAZ together with the variation of hardness. The results show similar tendencies between the ultimate tensile strength results and hardness, which also verified the validity of the microtensile test used here.

We selected the tensile curve for sample no. 12 in Fig. 5, the lower-bound value, as the representative HAZ tensile curve for the girth weldment in order to consider the influence of low strength on plastic collapse. The same method used to determine a representative HAZ tensile curve for the girth weldment was used to determine that of the seam weldment. The yield strength of HAZ was about 20 and 30% below those of the weld metal in the girth and seam weldment, respectively. The HAZ has lower strength than weld metal

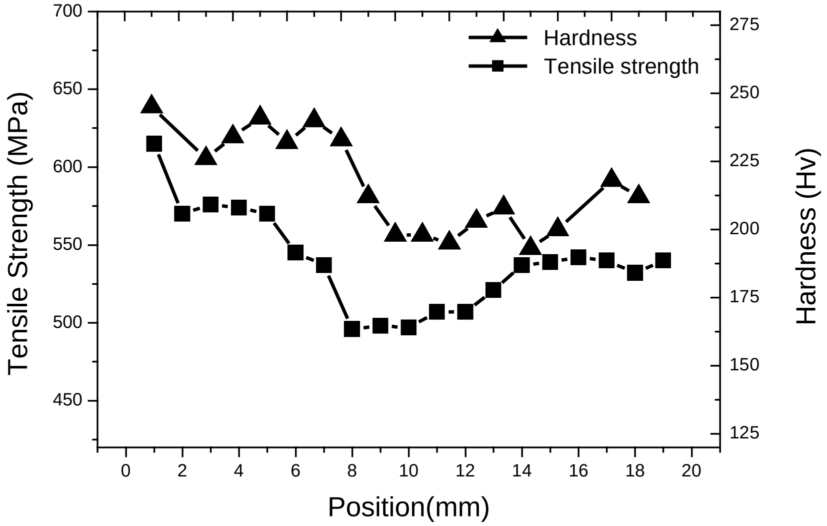

Fig. 7. Variation of ultimate tensile strength and variation of hardness.

because of the HAZ softening effect, which is due to decomposition of martensite by over-tempering: the high temperatures of the welding process alter the hard low-temperature transformation products to soft high-temperature products [10,11,14]. Since yield strength generally indicates resistance to plastic collapse, this means that the HAZ of this steel is more susceptible to plastic collapse than the weld metal.

The above results enable the influence of difference of material properties within weldment on resistance to plastic collapse to be handled more accurately in FADs.

3.2. Representative fracture toughness for evaluating resistance to elastic fracture

Table 5 lists representative fracture toughness values for the base metal, weld metal and HAZ. The CTOD values obtained were converted into K_{IC} values using Eq. (5) [4–6] (of the various equations for the conversion from CTOD to K_{IC} in current codes [4–6,13], this one is the least conservative for API X65-grade natural gas pipeline):

$$K_{IC} = \sqrt{\frac{2\sigma_Y E \delta_{IC}}{1-\nu^2}} \quad (5)$$

where δ_{IC} is critical CTOD and ν the Poisson's ratio.

As shown in Table 5, CTOD values have directionality: as a result of texture formed during TMCP [8], the CTOD in the circumferential direction (L-S) was higher than that in the longitudinal direction (T-S). Due to this directionality, a plastic zone can be generated only in the region that includes a dislocation slip system. Plastic zone formation increases fracture toughness since resistance to crack propagation is increased. In the natural gas pipeline studied here, it can be noted that a texture structure enhancing dislocation slip formed more in the circumferential than in the longitudinal direction. Additionally, it has been reported that this phenomenon affects fracture toughness strongly but tensile properties only slightly [7,8]; hence there was directionality in fracture toughness but not in tensile properties. In the weld metal, the CTOD values were not necessarily higher than in the base metal since the weld materials were overmatched only in strength [15]: in the girth weldment, the weld metal CTOD values were lower than those of the base metal, but in the seam weldment, the former were nearly the same as the latter. As shown in Table 5, the HAZ toughness is about 25–40 and 45% lower than that of weld metal in girth and seam weldment, respectively, which means that the HAZ is more susceptible than the weld metal to elastic fracture. The lower fracture toughness of the HAZ than weld metal is due to its combination of coarse-grained microstructure and the martensite–austenite constituents produced by the high temperatures of the welding process (above A_{C3} [9–11,14]).

Table 5
Fracture toughness of natural gas pipeline

Region	Location of crack tip	CTOD (mm)	K_{IC} (MPa $m^{0.5}$)
Base metal			
Girth weldment (circumferential crack)	Upper	0.40	300
	Middle	0.66	363
	Lower	0.44	315
Seam weldment (longitudinal crack)	Upper	0.26	242
	Middle	0.33	257
	Lower	0.23	228
Weld metal			
Girth weldment	Upper	0.29	268
	Middle	0.16	199
	Lower	0.43	326
Seam weldment	All	0.27	267
HAZ			
Girth weldment	All	0.12	153
Seam weldment	All	0.12	148

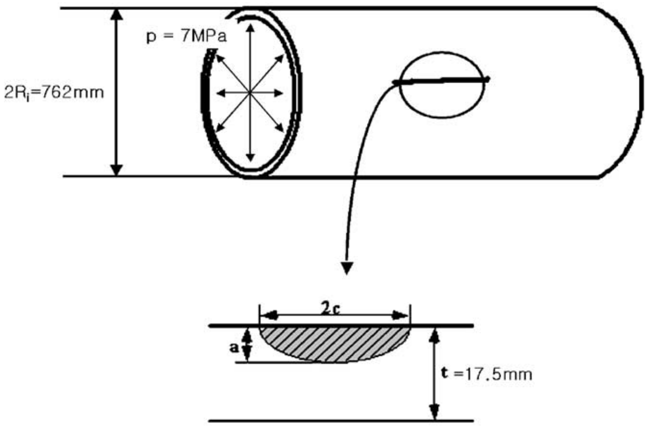

Fig. 8. Shapes of natural gas pipeline and longitudinal crack.

The above results enable the influence of difference of material properties within weldment on resistance to elastic fracture to be handled more accurately in FADs.

3.3. Comparison of crack assessment results

FFS assessment was performed for longitudinal surface flaws existing in natural gas pipeline weldments using the tensile properties and fracture toughness values obtained here. Fig. 8 shows schematic diagrams of natural gas pipeline and a target flaw. Only internal pressure was assumed as an applied force, since this is the dominant force on the pipeline. Additionally, since hoop stress due to internal pressure is twice as large in pipelines as axial stress, a longitudinal crack was selected as the target flaw. Because flaw depth is more important in natural gas pipeline than flaw length, flaw length is fixed at 800 mm and only flaw depth is varied.

Fig. 9 is a level 1 FAD for flaws in the base metal and weld metal. When constructing the FAD for base metal, the tensile properties of the middle region in Table 3 were applied to the 10 mm crack and those of the lower region were applied to 12, 13, 14 and 14.1 mm cracks. In addition, since

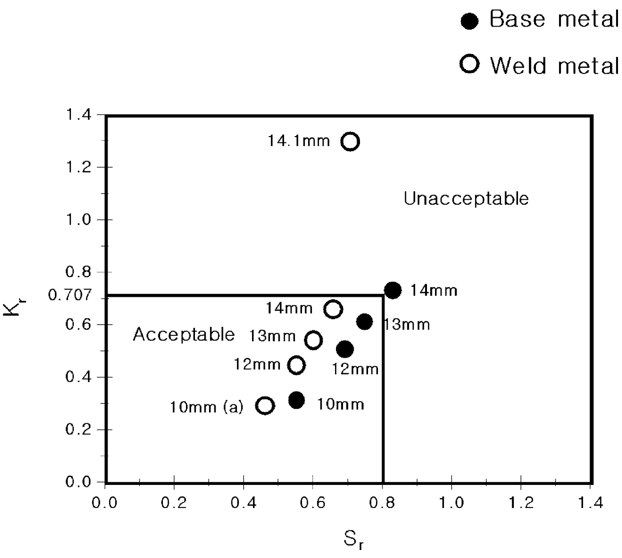

Fig. 9. Level 1 FAD for base metal and weld metal.

fracture toughness has directionality, longitudinal middle toughness was applied to the 10 mm crack and longitudinal lower toughness to the others. In the FAD for weld metal, the material properties of the seam weldment, which is parallel to the crack direction, were used to plot the assessment point. The level 1 FAD indicates that the weld metal is more susceptible to elastic fracture than base metal and that the base metal is more susceptible to plastic collapse than the weld metal. In the base metal, the 14 mm deep crack was unacceptable, but in the weld metal, the 14 mm crack was acceptable and the crack deeper than 14 mm was evaluated as experiencing abrupt elastic fracture.

These unacceptable cracks must be reassessed in a level 2 FAD, as in Fig. 10. As for level 1, the tensile properties and fracture toughnesses proper to crack locations were used to construct this level 2 FAD. Fig. 10 shows that unacceptable cracks in the level 1 FAD were also located outside level 2 FAC. But the safety margin was increased for the 14 mm crack in the weld metal, indicating that the level 2 FAD is less conservative than the level 1 FAD.

To assess FFS more accurately, the above cracks were assessed in a level 3 FAD (Fig. 11). Since the level 3 FAC includes tensile properties as a variable, the FAD for base metal differs from that for weld metal. In the FAD for base metal (Fig. 11a), since the assessment point of the 14 mm crack was located inside the FAC, the crack was acceptable, and the pipeline with this crack can be used without repair. But the FAD for the weld metal (Fig. 11b) shows that the 14.1 mm crack is unacceptable even in level 3 and that repair or replacement with fresh material is required.

It can easily be seen from the above that crack assessment results can be strongly affected by crack location, i.e. the representative mechanical properties of the regions containing cracks. Thus a crack within the HAZ produces quite different results from the results according to current FAD codes, which suggest that weld metal properties instead of HAZ properties can be used for flaws in the HAZ. This study constructed an HAZ-focused FAD using lower-bound HAZ properties from microtensile tests and HAZ-notched CTOD tests. Fig. 12 shows the results for cracks existing in HAZ using FAD of current codes and our HAZ-focused FAD. The HAZ-focused FAD differs from the current code FAD in two respects. First, the FAC for the HAZ does not overlap the FAC for weld metal. Second, the assessment points (L_r, K_r) for the weld metal and HAZ are not the same. In particular, the 13 mm deep flaw was located in an acceptable region of the FAD based on weld metal properties but in an unacceptable region of the FAD based on HAZ properties: the conventional FAD can be extremely non-conservative and

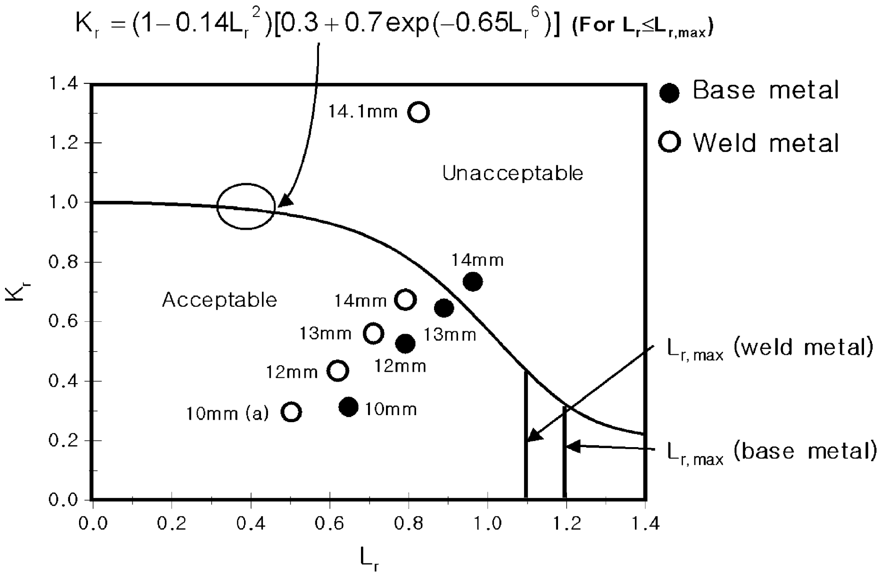

Fig. 10. Level 2 FAD for base metal and weld metal.

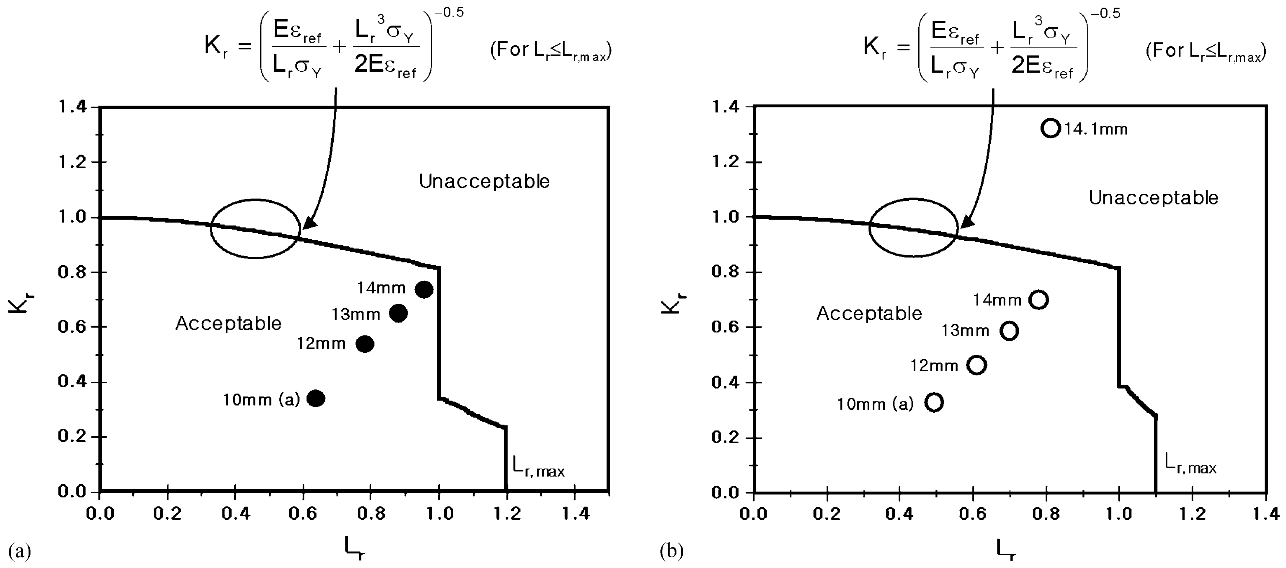

Fig. 11. Level 3 FAD for: (a) base metal and (b) weld metal.

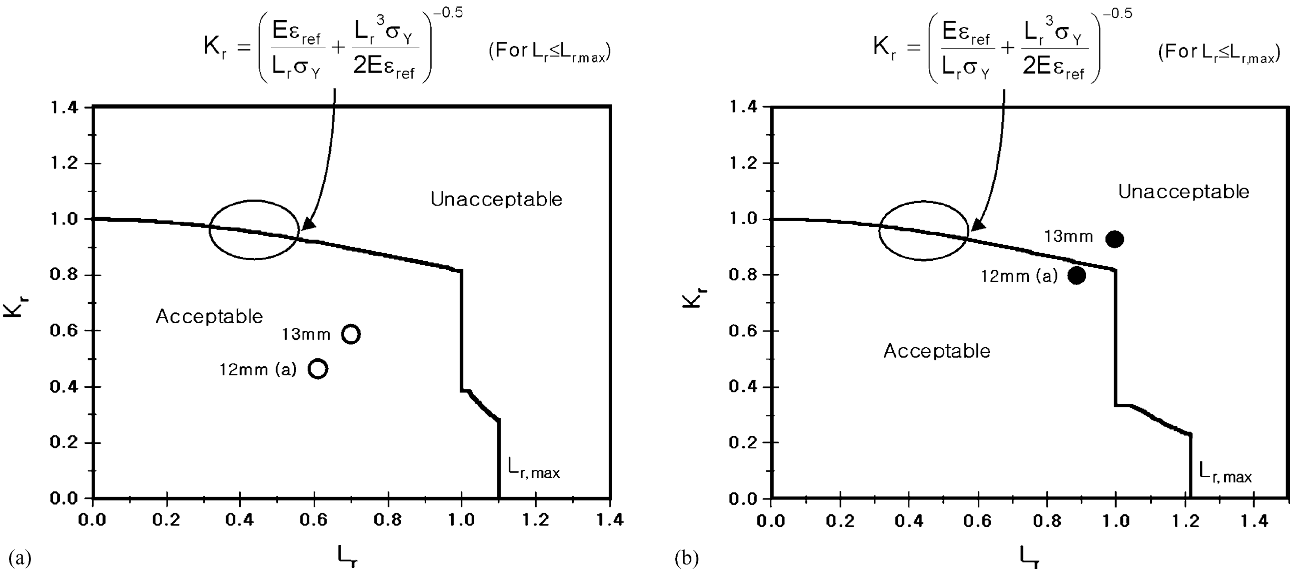

Fig. 12. Material-specific FADs based on: (a) weld metal and (b) HAZ properties.

includes serious risk for HAZ crack assessment. It can thus be seen that, when flaws are found in the HAZ, the properties of the HAZ itself and not those of weld metal must be used to construct the FAD.

4. Conclusions

In this study, tensile properties and fracture toughness of base metal, weld metal and HAZ were evaluated individually. In particular, HAZ properties were evaluated accurately by microtensile tests and HAZ-notched CTOD tests. The material properties obtained for each region were used to construct appropriate FADs and the crack assessment results using the FADs were compared. It was found that the assessment results are strongly dependent on local variations in mechanical properties, i.e., crack location. In particular, it was shown that, since HAZ of this pipeline shows 20% (girth) and 30% (seam) lower yield strength and about 25–40% (girth) and 45% (seam) lower toughness than weld metal, the HAZ-focused FAD yields far different results from the conventional FAD that uses weld metal properties instead of HAZ properties. This indicates that the HAZ-focused FAD can avoid possible serious errors generated by the use of conventional FAD for flaws in the HAZ.

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