Materials Science and Engineering A 546 (2012) 258–262

Contents lists available at SciVerse ScienceDirect

Materials Science and Engineering A

journal homepage: www.elsevier.com/locate/msea

Variations in DBTT and CTOD within weld heat-affected zone of API X65 pipeline steel

Jang-Bog Ju [a], Woo-sik Kim [b], Jae-il Jang [c,*]

[a] Samsung Electronics Co. Ltd., Asan 336-841, Republic of Korea
[b] Research & Development Center, Korea Gas Corporation, Ansan 425-150, Republic of Korea
[c] Division of Materials Science and Engineering, Hanyang University, Seoul 133-791, Republic of Korea

ARTICLE INFO

Article history:
Received 15 February 2012
Received in revised form 14 March 2012
Accepted 17 March 2012
Available online 26 March 2012

Keywords:
Fracture toughness
CTOD
DBTT
Pipeline steel
Weld heat-affected zone

ABSTRACT

The fracture resistance of heat-affected zones (HAZs) in girth welded joint of API X65 steel pipeline was systematically investigated. While the change in Charpy impact energy has been typically evaluated in previous studies, here the variations in ductile-to-brittle temperature (DBTT) and crack-tip opening displacement (CTOD) within HAZ were explored. A series of experiments revealed that both values vary dramatically (i.e., DBTT increases and CTOD decreases) as the location approaches the fusion line (FL) and thus the region adjacent to FL exhibited the lowest CTOD and highest DBTT, possibly due to the increasing portion of coarse-grained HAZ. Interestingly, however, even the FL regions still showed moderate toughness at $-40\,^{\circ}\mathrm{C} \sim$ room temperature. Microstructural analysis and additional impact tests using simulated HAZ specimens suggested a possibility that fine-grained HAZs with higher toughness may suppress the brittle fracture from neighboring coarse-grained region.

1. Introduction

Combination of high strength and good toughness is essential for the steels used in pipelines for transporting crucial oil and natural gas over a long distance. However, the steels' excellent mechanical properties (usually offered by thermo-mechanical controlling process, TMCP) can be upset during multi-pass welding procedure, because welding thermal cycles can significantly change microstructures and in turn mechanical properties [1–9]. Especially, the fracture characteristics of weld heat-affected zones (HAZs) should be carefully examined with both metallurgical and mechanical viewpoints, because the HAZs generally show not only a rapid gradient of microstructures but also unusual mechanical environments such as welding residual stresses and strength mismatch between weld metal and base metal (for example, see [10–13]).

Considerable efforts have been made to analyze the fracture resistance of welded joints in pipeline through full-scale burst tests or small-scale standard toughness tests [1–9]. In previous studies on actual HAZ toughness, the variation in Charpy V-notch impact energy within HAZ has been the most popularly evaluated because of the advantages of impact test such as simple and easy procedures of the sample preparation, testing, and data analysis. However, impact energy is not fracture-mechanics-based but empirical measure of toughness so that its practical application is limited to pre-qualification purpose (i.e., judging whether or not the welds satisfy the quality requirement). Therefore, for better understanding of fracture characteristics in pipeline weld HAZ, evaluation of other toughness values seems to be needed; e.g., fracture-mechanics-based toughness (such as K_{IC}, J_{IC}, and critical crack-tip opening displacement, CTOD) is essential for fitness-for-service assessment of pipeline crack [2]. Also, estimation of the ductile-to-brittle temperature (DBTT) can provide important information about the extremity of applicable environment. Very recently, Nazari et al. [14–16] reported that the DBTT of functionally graded steels can be seriously affected by complex nature of their layered microstructures, which may indicate a need to analyze the variation in DBTT within weld HAZs showing rapid microstructural gradients.

With this in mind, in the present study, the variations in DBTT and CTOD within actual HAZ of girth weld joint in API X65-graded pipeline (used as main pipeline for natural gas transmission in Korea) were systematically explored. In addition to actual HAZ specimens, simulated HAZ specimens were also tested to examine the mechanism of HAZ toughness change in more detail. In this study, our attention was paid to girth welds (rather than seam welds) based on a simple assumption that the probability of flaw generation in girth welds can be higher than that in seam welds since girth welding is often manually conducted at pipeline construction sites. It is also notable that mechanical behavior of girth

* Corresponding author.
E-mail address: jijang@hanyang.ac.kr (J.-i. Jang).

0921-5093/$ – see front matter
doi:10.1016/j.msea.2012.03.062

welds under longitudinal stresses gathers increasing interests due to the recent demand for 'strain-based design' pipeline.

2. Experimental

A 17.5-mm-thick weldment of API X65 steel (whose yield strength is higher than 65 ksi or ~450 MPa, and chemical composition is Fe–1.45Mn–0.08C–0.019P–0.003S–0.31Si in weight %) was prepared under the same welding condition as that employed for girth welding during construction of main natural gas transmission pipeline in Korea; gas tungsten arc welding (GTAW) followed by shielded metal arc welding (SMAW) with a heat input in the range of 5–30 kJ/cm. No significant defects were found in the welds by non-destructive X-ray examination.

Both Charpy V-notch impact tests and CTOD tests were carried out for four different locations within HAZ from the fusion line (FL that is apparent boundary between weld metal and HAZ, and was roughly determined by a macro-etching with 2% Nital solution in this study) to the unaffected base metal; FL, FL + 1 mm, FL + 3 mm, and FL + 5 mm. Charpy impact tests were conducted according to ASTM E23 standard [17]. Standard 2 mm-V-notched specimens were tested by a Tinius Olsen impact tester (Horsham, PA, USA) of 407 J capacity at various temperatures from −120 °C to room temperature (RT). CTOD experiments were performed in accordance with ASTM E1290 standard [18]. Standard 3-point single edge notched bending (SENB) specimens having through-thickness fatigue precrack were tested with a MTS universal testing machine (Eden Prairie, MN, USA) at −40 °C and RT. Impact tests were also performed on simulated HAZ samples which were prepared by applying thermal cycles to base metal samples using a Gleeble 1500 thermomechanical simulator (Dynamic Systems Inc., Poestenkill, NY). Microstructures and fractured surfaces were examined by an optical microscope (Olympus Corp., Tokyo, Japan) and a scanning electron microscope (SEM, JSM-6330F, JEOL Ltd., Tokyo, Japan), respectively, using the samples prepared by conventional metallographic techniques.

3. Results and discussion

A series of impact tests were performed at various temperatures to observe ductile-to-brittle transition behavior for four different HAZ locations, and the results are shown in Fig. 1a. It is obvious that the impact toughness decreases as the notch location approaches FL: Averaged value of the absorbed impact energy for FL + 1 mm ~ FL + 5 mm is constant as 407 J (that is the maximum capacity of the used equipment) at both RT and 0 °C, and rapidly decreases to 240 J (at RT) and 138 J (at 0 °C) for FL. At −40 °C, average impact energy dramatically decreases with approaching FL, and is the lowest, but still moderate, value of ~63 J at FL. Note that, according to the specification of API 5L [19] for the 16–20 mm-thickness pipelines, the required minimum impact energy at 0 °C is 27 J, and thus all specimens in Fig. 1a satisfy the API requirement. From the data in Fig. 1a, the DBTT (or energy transition temperature, ETT) was estimated as the temperature corresponding to the mean value of upper-shelf energy (at RT) and lower-shelf energy (that is close to 0 J for all specimens of FL ~ FL + 5 mm). The results are summarized in Fig. 1b where, as the location approaches FL, the DBTT rapidly increases (i.e., fracture resistance decreases) from −87 °C (for FL + 5 mm) to −12 °C (for FL). It is interesting to note that both measure of fracture resistance (impact energy and DBTT) varied together with reducing the distance from FL, because the change in upper-shelf impact energy does not need to accompany the change in DBTT.

In order to obtain the fracture-mechanical toughness, CTOD tests were performed for the different precrack locations within HAZ. It is noteworthy that the shape of precrack tip introduced in weld CTOD specimen can be seriously irregular, which can lead to wrong value of critical CTOD [20]. In this study, post-test examination revealed that all used CTOD specimens were free from the issues related with the irregular-shaped precrack tip (see an example shown in inset of Fig. 2), possibly because the specimen is not so thick and thus residual stresses through thickness are not so serious. Fig. 2 shows the variation in CTOD toughness as a function of the precrack positions. The critical CTOD decreases as the precrack location approaches FL, but the regions near FL still exhibit moderate values of critical CTOD, which is similar to the trends of Charpy test results described above. We will return to this later.

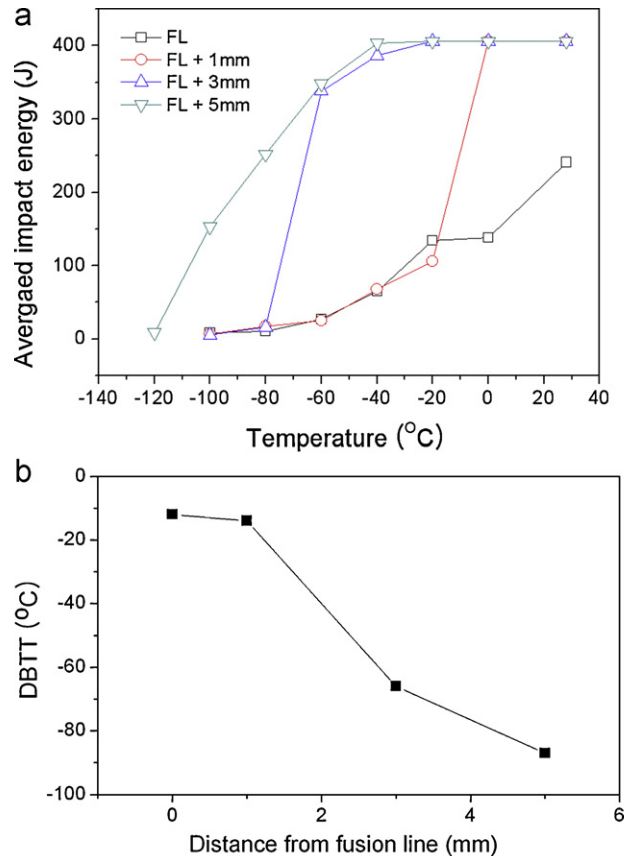

Fig. 1. Results of Charpy impact tests: (a) variation in averaged impact energy as a function of testing temperature; (b) DBTT change with the notch location.

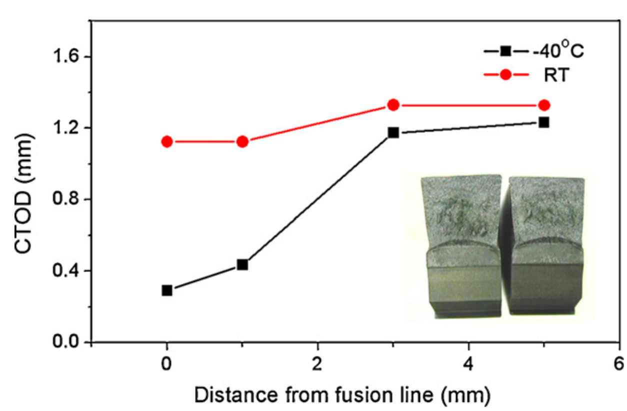

Fig. 2. CTOD change with the precrack location. Inset image shows an example of the regular-shaped precrack of the CTOD specimen.

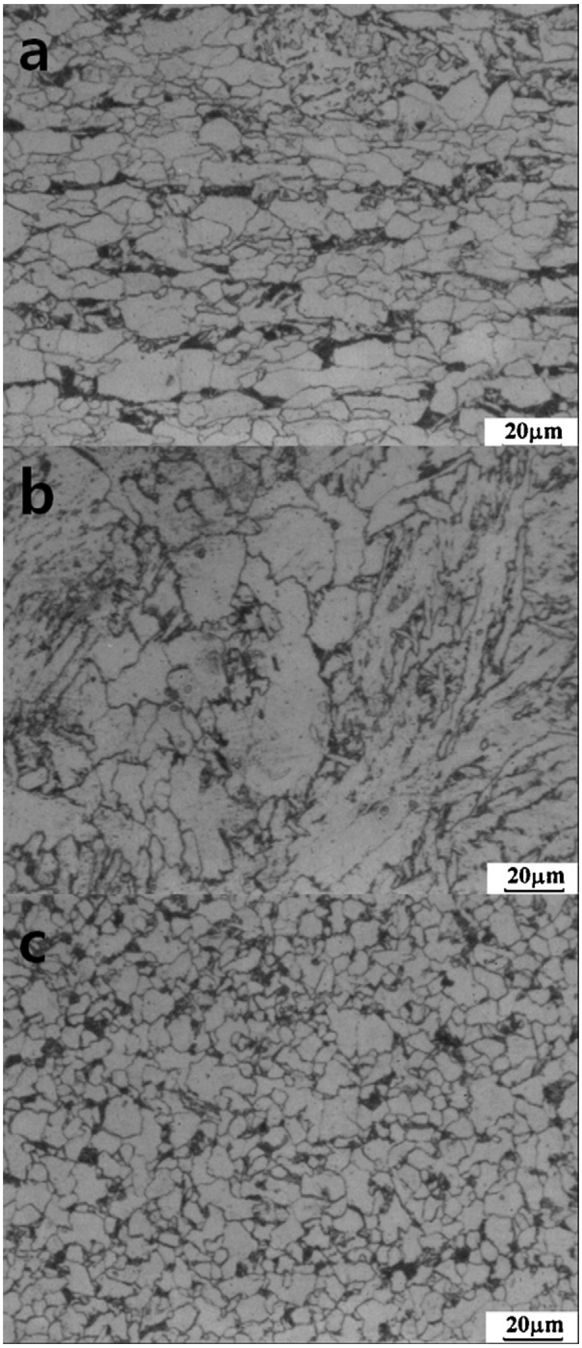

Fig. 3. Microstructural change within HAZ: (a) base metal, (b) CGHAZ region, and (c) FGHAZ region.

The toughness variation within HAZ has been typically analyzed in terms of the complex microstructural gradient of HAZ. Fig. 3 provides representative microstructures of base metal and specific HAZ regions examined in this work. The microstructure of base metal consists of polygonal (and acicular) ferrite and pearlite, as seen in Fig. 3a. A region mainly consisting of coarse bainite (referred to as coarse-grained HAZ, CGHAZ) are observed near FL (Fig. 3b), while some region exhibits recrystallized fine grains, so-called fine-grained HAZ or FGHAZ (Fig. 3c) whose grain size is much smaller than that of base metal. Since the CGHAZs are expected to show very low toughness due to large grain size, the portion of the CGHAZ in precrack tip of CTOD sample was carefully measured through post-test sample sectioning procedure [11]. As seen in Fig. 4, the FL and FL + 1 mm specimens (showing the lowest CTOD and highest DBTT)

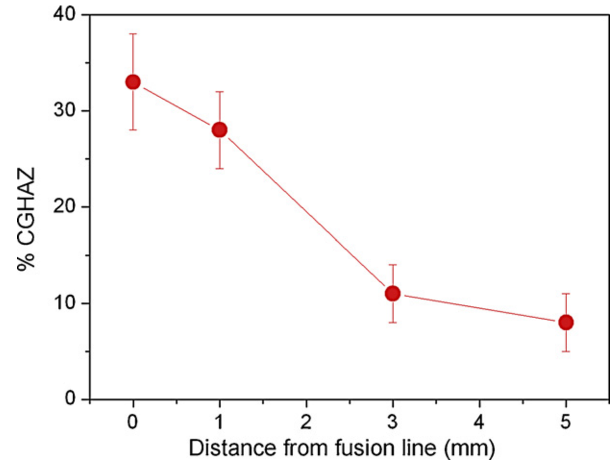

Fig. 4. Fraction of CGHAZ in the precrack tip.

exhibit the largest portion of the CGHAZ in precrack tip. Therefore, it is reasonable to believe that low toughness near FL is indeed associated with high portion of CGHAZ in the region, as well accepted in previous literature [9–12].

To analyze how much CGHAZ affects actual HAZ toughness in more detail, additional Charpy impact tests were performed on simulated HAZ samples. In general, a certain HAZ region experiences three or four welding thermal cycles during multi-pass welding process. Among the cycles, the first and second cycles may seriously change the microstructure of the region, whereas the effects of third and fourth cycles on the microstructure are very limited due to their low peak temperature. The HAZ microstructures exposed to the first thermal cycle are typically categorized into four groups based on the peak temperature (T_{P1}): CGHAZ ($T_{P1} > \sim 1100\,°C$), FGHAZ ($1100\,°C > T_{P1} > A_{C3}$), intercritical HAZ (ICHAZ: $A_{C3} > T_{P1} > A_{C1}$), and subcritical HAZ (SCHAZ: $A_{C1} > T_{P1} > 450\,°C$) [11,12]. According to the peak temperature of subsequent thermal cycle (T_{P2}) in multi-pass welding procedure, the CGHAZ can be divided again into four characteristic regions: unaltered (UA) CGHAZ with $T_{P2} > 1100\,°C$, supercritically reheated (SCR) CGHAZ with $1100\,°C > T_{P2} > A_{C3}$, intercritically reheated (IC) CGHAZ with $A_{C3} > T_{P2} > A_{C1}$, and subcritically reheated (SC, or tempered) CGHAZ with $A_{C1} > T_{P2} > 450\,°C$ [11,12]. Among them, SCR CGHAZ can be treated as FGHAZ due to its recrystallized fine grain, while SC CGHAZ is often considered as the same as UA CGHAZ since toughness and microstructure of the former are usually very close to those of the latter [12]. IC CGHAZ is generally considered

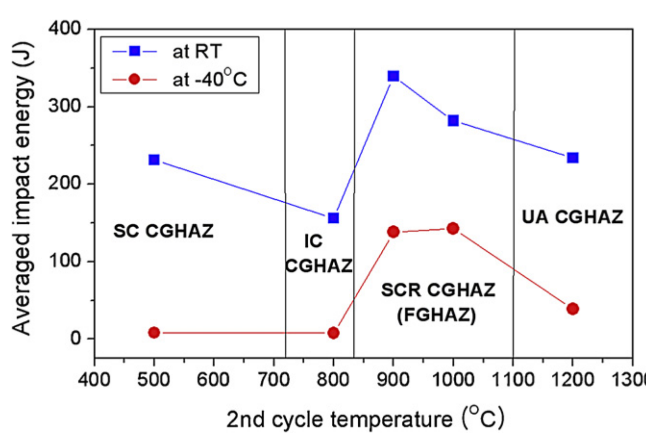

Fig. 5. Change in impact energy of simulated HAZ specimens as a function of the second peak temperature.

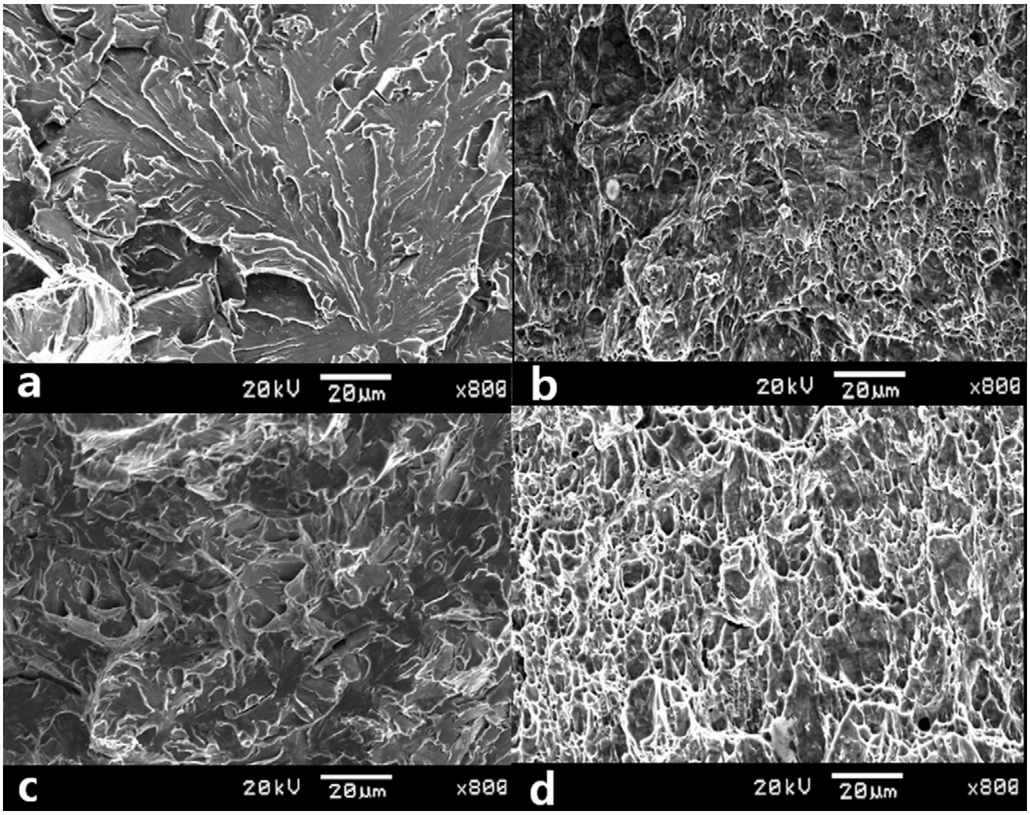

Fig. 6. SEM fractographs of simulated HAZ specimens: (a) IC CGHAZ at −40 °C and (b) RT, (c) FGHAZ at −40 °C and (d) RT.

as a primary local brittle zone (LBZ) because it exhibits very low toughness due to a large portion of martensite–austenite (M–A) constituent in addition to the coarse bainite structure [9–13]. Based upon this categorization, we produced simulated HAZ specimens (with $A_{C1} = 720\,°C$ and $A_{C3} = 828\,°C$ that were measured through dilatometer tests) and evaluated their impact toughness. Detailed procedure to prepare the simulated HAZ samples is explained elsewhere [11,12]. Fig. 5 shows the impact test results as a function of T_{P2}. The UA CGHAZ, IC CGHAZ, and SC CGHAZ have relatively low toughness values at RT and very low impact values at −40 °C, whereas SCR CGHAZ having recrystallized fine grains shows much higher toughness at both RT and −40 °C. Fig. 6 shows typical examples of SEM fractographs for IC CGHAZ and FGHAZ that have the lowest and highest toughness respectively. The evidence for cleavage fracture is clear for the lowest toughness case (IC CGHAZ at −40 °C; Fig. 6a), while fine dimples indicating ductile fracture are observed for the highest toughness case (FGHAZ at RT; Fig. 6d). The IC CGHAZ at RT and FGHAZ at −40 °C (that show similar toughness to each other) indicate quasi-cleavage-typed fracture surface (Fig. 6b and c).

Comparison of the impact toughness in Fig. 1 (for actual HAZ) with those in Fig. 5 (for simulated HAZs) revealed that the toughness of FL sample is higher than the average toughness of the simulated CGHAZ (including UA CGHAZ, SC CGHAZ, and IC CGHAZ). This suggests a possibility that FGHAZs with higher toughness may suppress the brittle fracture from neighboring CGHAZs. This hypothesis can explain why the regions near FL have the lowest but still 'moderate' values of CTOD and impact energy at RT ~ −40 °C (in Figs. 1a and 2) despite the large fraction of CGHAZ in the regions. From this scenario, one may also imagine that the HAZ toughness including CTOD and DBTT, at least in this study, is conceivably controlled by rube-of-mixture of microstructures in the notch or precrack tip instead of a weakest-link microstructure such as LBZs; i.e., toughness is not dominated by CGHAZ alone, but is also affected by other surrounding microstructures like FGHAZ. This is in an agreement with our previous study [13] suggesting that a LBZ-based analysis may conceivably be overconservative for predicting the practical safety performance of welded structures.

4. Conclusions

In the present work, the variations in DBTT and CTOD within HAZ of girth welded joint in API X65 steel pipeline were systematically explored. Both values varied dramatically with the distance from FL, and the region near FL exhibited the lowest CTOD and highest DBTT, which is possibly due to the increasing portion of coarse-grained HAZ. Nonetheless, interestingly, even the FL regions showed still moderate toughness values at −40 °C ~ RT. This behavior was discussed in terms of microstructural changes, which were analyzed through additional tests with simulated HAZ specimens. From the results, it was proposed that fine-grained HAZs with higher toughness may suppress the brittle fracture from neighboring coarse-grained region.

Acknowledgments

This work was sponsored by Korea Gas Corporation (KOGAS), and in part by the Human Resources Development of the Korea Institute of Energy Technology Evaluation and Planning (KETEP) grant funded by the Korea government Ministry of knowledge Economy (No. 20114010203020).

References

[1] J.-S. Lee, J.-B. Ju, J.-I. Jang, W.-S. Kim, D. Kwon, Mater. Sci. Eng. A 373 (2004) 122–130.

[2] J.-I. Jang, Y. Choi, J.-S. Lee, Y.-H. Lee, D. Kwon, M. Dao, R. Kania, Int. J. Fract. 131 (2005) 15–34.
[3] N. Ishikawa, T. Shinmiya, S. Igi, J. Kondo, Proceedings of IPC 2006, 6th International Pipeline Conference, Calgary, Alberta, Canada, 2006 (Article No. IPC 2006-10245).
[4] J.A. Gianetto, J.T. Bowker, R. Bouchard, D.V. Dorling, D. Horsley, Proceedings of IPC 2006, 6th International Pipeline Conference, Calgary, Alberta, Canada, 2006 (Article No. IPC 2006-10399).
[5] S.H. Hashemi, D. Mohammadyani, M. Pouranvari, S.M. Mousavizadeh, Fatigue Fract. Eng. Mater. Struct. 32 (2009) 33–40.
[6] H.K. Sung, S.Y. Shin, W. Cha, K. Oh, S. Lee, N.J. Kim, Korean J. Met. Mater. 48 (2010) 875–883.
[7] S.H. Hashemi, Mater. Sci. Eng. A 528 (2011) 1648–1655.
[8] H.K. Sung, S.Y. Shin, W. Cha, K. Oh, S. Lee, N.J. Kim, Mater. Sci. Eng. A 528 (2011) 3350–3357.
[9] C. Li, W. Wang, Y. Chen, J. Mater. Sci. 46 (2011) 6424–6431.
[10] B.C. Kim, S. Lee, N.J. Kim, D.Y. Lee, Metall. Mater. Trans. 22A (1991) 139.
[11] J.-I. Jang, J.-B. Ju, B.-W. Lee, D. Kwon, W.-S. Kim, Mater. Sci. Eng. A 340 (2003) 68–79.
[12] J.-I. Jang, J.-S. Lee, J.-B. Ju, B.-W. Lee, D. Kwon, W.-S. Kim, Mater. Sci. Eng. A 351 (2003) 183–189.
[13] J.-I. Jang, B.-W. Lee, J.-B. Ju, D. Kwon, W.-S. Kim, Metall. Mater. Trans. A 33 (2002) 2615–2622.
[14] A. Nazari, A.A. Milani, Mater. Sci. Eng. A 528 (2011) 3854–3859.
[15] A. Nazari, A.A. Milani, M. Zakeri, Comput. Mater. Sci. 50 (2011) 2028–2037.
[16] A. Nazari, A.A. Milani, J. Mater. Sci. 46 (2011) 6007–6017.
[17] ASTM E23, Standard Test Methods for Notched Bar Impact Testing of Metallic Materials, ASTM International, West Conshohocken, PA, 2007.
[18] ASTM E1290, Standard Test Method for Crack-Tip Opening Displacement (CTOD) Fracture Toughness Measurement, ASTM, International, West Conshohocken, 2008.
[19] API Specification 5L, American Petroleum Institute, Washington, DC, 2000.
[20] J.-I. Jang, Y.-C. Yang, W.-S. Kim, D. Kwon, Met. Mater. 4 (1997) 230–238.