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Fracture analysis of axially flawed ring-shaped bending specimen

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Abstract

Application of pipelines is common in process industry and energetic facilities, as parts of storage and transport systems. Structural integrity and fracture resistance of the pipeline elements is typically assessed by testing fracture mechanics specimens, like compact tensile CT or single-edge notched bending, SENB. However, fabrication of these geometries is often not possible for thin-walled pressurized elements, commonly used in structures of process and energetic facilities. Therefore, some proposals for non-standard specimens have been given in the literature, differing by the position of the initial defects, in circumferential or axial direction, and by the degree of complexity of procedures for fabrication and testing.
Recently proposed ring-shaped specimen (PRNB - Pipe Ring Notched Bend) is used here to assess the fracture resistance of pressurized cylinders with defects in axial direction, critical for the internal pressure loading. The specimens are simple to fabricate and have the same material history as the actual structure, such as thermo-mechanical treatment, assembly or exploitation conditions. In this work, the ring specimens are cut from the thin-walled non-alloy steel pipes for pressure purposes. Experimental-numerical procedure is applied for prediction of fracture behavior. The methods include material characterization, fracture testing and micromechanical analysis of specimen failure. The results obtained so far lead to conclusion that PRNB specimen is a good option for testing of fracture resistance of pipelines and small-scale vessels.

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Keywords: Ductile fracture; Steel pipes; Stress concentrator; Micromechanical analysis.

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1. Introduction

Analysis of stress/strain state, fracture, integrity assessment and remaining service life of pipelines is an important topic for different industry branches. Many studies dealing with these issues on different process system elements are presented in literature, and some examples are: Dutta et al. (2005), Xu et al. (2010), Gubeljak et al. (2007), Marenić et al. (2010), Dimić et al. (2013), Medjo et al. (2012), Kozak et al. (2010), Sedmak et al. (2016), Martić et al. (2016). In exploitation, it is important to take into account the possible initial defects, caused by production, thermo-mechanical treatment, welding or assembly operations.

Experimental fracture testing of the pipeline material is typically difficult, because the standard requirements regarding the specimen and crack geometry cannot be fulfilled for all wall thicknesses. Therefore, some authors have previously proposed other test specimens, Xu et al. (2009), Mahajan et al. (2016), Koo et al. (2013), Gajdos and Sperl (2012) and Bergant et al. (2015), for defects in circumferential and axial direction. The main focus in this work is testing the fracture behavior of the seamless and seam thin-walled pipes with a defect in axial direction, by application of recently proposed pipe ring notched bending specimen (PRNB); Likeb et al. (2014), Gubeljak et al. (2014), Likeb (2014), Medjo et al. (2015).

2. Specimens, materials and micromechanical modeling

The drawing of a PRNB specimen and testing scheme are shown in Fig. 1, while Table 1 contains the dimensions of the examined specimens, produced from seam and seamless pipes. During the testing of the ring specimens, strains on the specimen surface and fracture mechanics parameters (CMOD - crack mouth opening displacement, and CTOD - crack tip opening displacement) are determined by stereometric measurement system Gom Aramis. CTOD is determined by using δ_5 concept, while crack growth is obtained by normalization technique.

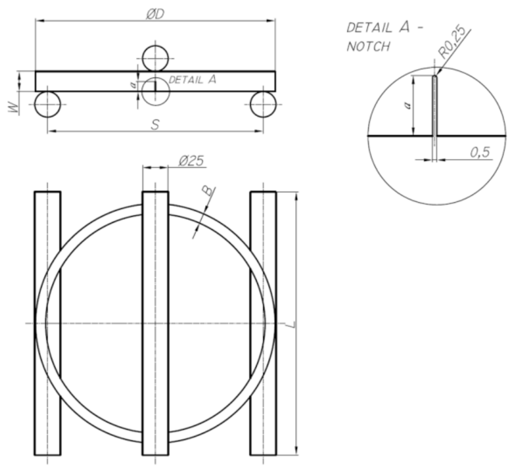

Fig. 1. Specimen dimensions and testing scheme

Table 1. Dimensions of specimens

	PRNB S-WM1	PRNB S-WM2	PRNB S-WM3	PRNB S-BM1	PRNB SL1
Pipe type	Seam (notches in WM and BM)	Seam (notches in WM and BM)	Seam (notches in WM and BM)	Seam (notches in BM)	Seamless (notches)
D_o [mm]	168.18	168.43	168.21	168.28	168.39
B [mm]	3.21	3.46	3.24	3.23	3.52
W [mm]	12.99	21.05	19.26	19.23	21.15
W/B [-]	≈ 4	≈ 6	≈ 6	≈ 6	≈ 6
a/W [-]	0.5	0.5	0.5	0.5	0.45
S (=0.9 D_o) [mm]	151.5	151.5	151.5	151.5	151.5

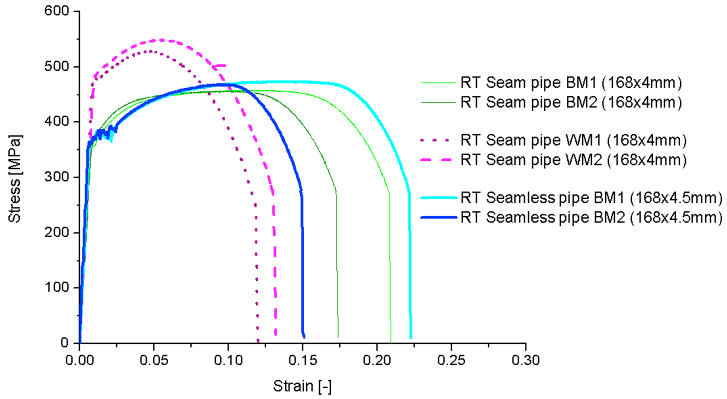

Fig. 2. Stress -strain curves - seamless (P235GH) and seam (P235TR1) steel pipes.

Engineering stress-strain curves for analyzed pipes are shown in Fig. 2; these are obtained by testing the round tensile specimens with diameter 2 mm. The seam and seamless pipes are fabricated from very similar materials, P235TR1 and P235GH, respectively. The strengths of the base metals (BM) of both pipes lie in rather small range (Fig. 2), while testing of the seam revealed a significant overmatch.

The fracture behavior is analyzed, in addition to experimental testing, by application of the micromechanical model CGM, Complete Gurson model, Zhang et al. (2000). The damage parameter in this model is porosity (f); its initial value for the examined materials, f_0, is set equal to the volume fraction of the larger particles (inclusions) in steel: seam pipe BM: f_v=0.02, seam pipe WM (weld metal): f_v=0.007, seamless pipe BM: f_v=0.007. The complete Gurson model is applied in numerical analysis by using Simulia Abaqus software with user material subroutine created by Z.L. Zhang.

3. Results and discussion

Fracture resistance curves (CTOD-Δa) obtained by experimental testing of the analyzed specimens are shown in Fig. 3. Difference between the seam and seamless pipes is observed - generally, the curve for the seamless pipe (specimen PRNB SL1) is above the range obtained for both WM and BM of the seam pipes. For the seam pipes, difference between the fracture behavior between the base metal (S-BM1) and weld metal (spec. S-WM1, S-WM2 and S-WM3) is observed.

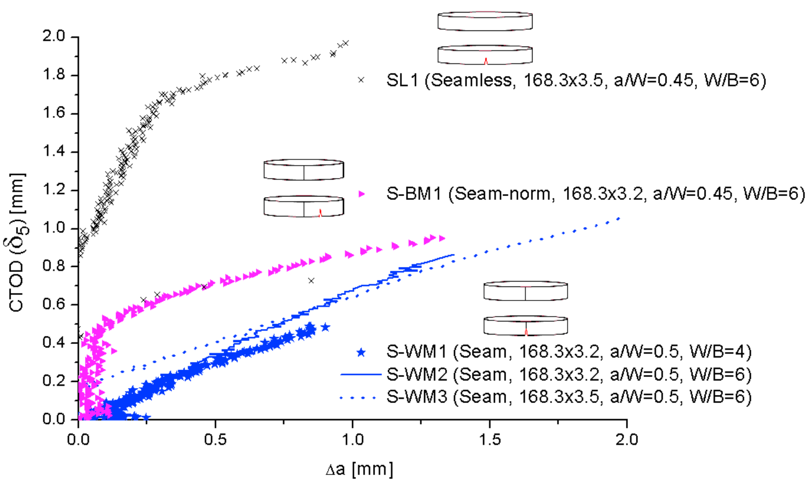

Fig. 3. CTOD-Δa curves.

For the curves representing the seam pipes with one of the notches in the seam (spec. S-WM1, S-WM2 and S-WM3), a good agreement is obtained, with different final crack lengths for 3 specimens (depends to some extent of the moment of experiment stopping). Therefore, repeatability of the results is confirmed. Another conclusion is a small influence of the ratio *W/B* and wall thickness *B*, and also ratio *a/W*, on fracture resistance. Larger specimen width (i.e. higher ratio *W/B*) result in a more pronounced crack growth, while these dimensions do not affect the curve slope.

Regarding the small influence of the crack length on fracture resistance of the ring-shaped specimens, it was also shown on the example of NIMOL 490K steel in Musraty et al. (2017) - this can be regarded as an advantage of ring-shaped specimen, having in mind that the crack length affects the fracture resistance of some standard fracture specimens.

Experimental results point out to the dominant influence of material, and not the specimen geometry (diameter, wall thickness, specimen width and crack/notch length) - which is favorable for application of PRNB specimen in determining the fracture toughness. The seam and seamless pipes (base metal) have similar tensile properties, while the testing of ring shaped specimens revealed differences in fracture resistance.

The finite element (FE) models of the ring specimens with notches in BM are formed by applying two planes of symmetry, resulting in a quarter-symmetry geometry, Fig. 4a. In micromechanical analysis of fracture of seamless pipes, transferability of micromechanical parameters is achieved - the fracture resistance curve in Fig. 4b is obtained by transferring the micromechanical parameters (initial porosity f_0 and finite element size) from the CT specimens fabricated from a seamless pipe with a thicker wall (133x11mm).

Micromechanical analysis of the fracture of seam pipe rings with both notches in the base metal (i.e. plane of the notches is at an angle of 90° with respect to the seam) has shown that significantly smaller element size is adequate for this material, in comparison with the seamless pipe of similar dimensions. Here, the appropriate value turned out to be 0.15 mm, as shown in Fig. 5a. This result, i.e. appropriate FE size, is utilized (transferred) in the analysis of the seam pipes with a notch in the seam and a notch in the weld metal. Due to the geometry of this specimen (one notch in BM and one in WM), one symmetry plane is applied - half-model. Each side of the specimen is modeled with its own appropriate element size and material properties.

It turns out that the weld metal requires three times smaller element then the base metal of the seam pipe - 0.05 mm in comparison with 0.15 mm for the base metal. The curves obtained using the CGM are shown in Fig. 5b.

Having in mind the calculation times, primarily due to the small element size in WM, a possibility of forming a simplified model with quarter-geometry is considered (in addition to the model representing a half of the ring). This simplification would correspond to a hypothetical pipe with the same geometry, but with two weld metals. It turns out that the simplified quarter-model can successfully be used for prediction of damage development through the weld metal, with significant decrease in computation time and resources.

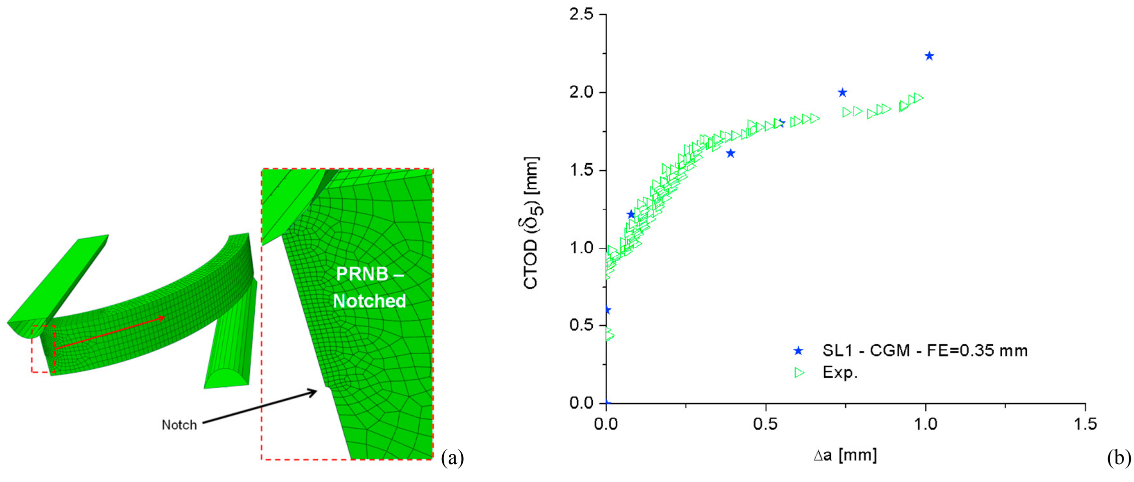

Fig. 4. Finite element mesh of the PRNB specimen (a) and crack resistance curve for specimen PRNB SL1 (b)

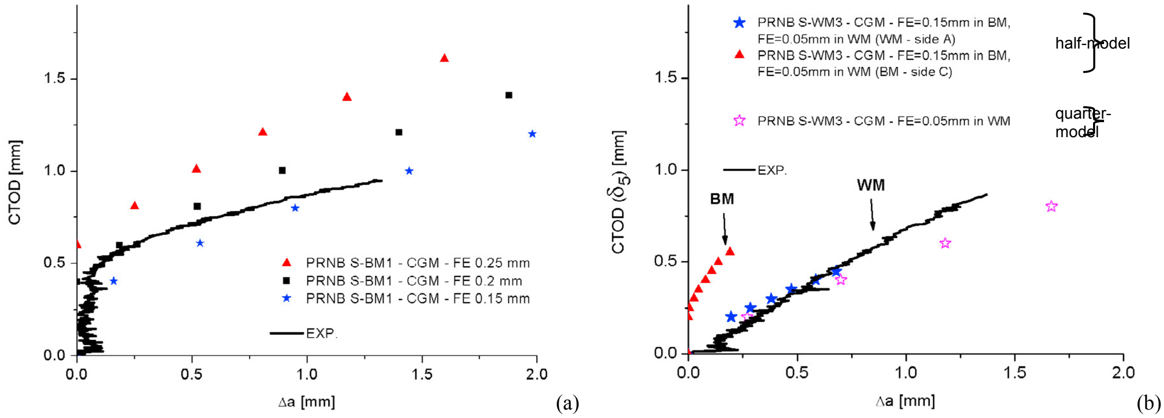

Fig. 5. Crack resistance curves - specimens S-BM1 (notches in BM) (a) and S-WM3 (notches in BM - side C, and WM, side A) (b)

Fig. 6. Fracture surfaces of a notched (a) and pre-cracked (b) ring-shaped specimen.

If the pre-cracking is applied on the ring specimens (in order to apply the procedure used for standard CT and SENB specimens), the pre-crack is not equally formed along the thickness. An example is shown in Fig. 6; a notched specimen fracture surface is shown in Fig. 6a, while Fig. 6b represents a pre-cracked specimen. The advantage of pre-cracking is higher stress triaxiality, and therefore better conditions for ductile fracture initiation, while the uneven fracture surface is its down-side. However, despite the lack of a sharp crack and thin wall (unfavorable for ductile damage development), ductile crack growth is obtained in all specimens considered here. More details about the influence of the stress concentrator shape will be reported elsewhere.

4. Conclusions

The topic of this work is damage and fracture characterization of the pipeline material using recently proposed Pipe ring notched bend (PRNB) specimens. Fracture analysis is performed on seam and seamless pipes, commonly used for pressure applications in chemical plants and energetic facilities. Initial defects in the pipeline material (machined notches) were positioned in the seam or in the base metal.

On the example of a group of specimens, a good repeatability of the results is obtained, and also small dependence on notch length, specimen thickness and width and wall thickness. Briefly, it can be said that PRNB specimens were successfully used for assessment of difference in failure resistance of the materials of the seam and seamless pipes. Also, they enabled the estimate of the level of heterogeneity, on the example of the seam specimens with notches in BM only and notches in BM and WM. Micromechanical analysis has shown that the model for ductile crack growth assessment (CGM) can capture the trends obtained by testing the specimens from seam and seamless pipe. The micromechanical parameters, initial porosity and finite element size, are transferred between the CT and PRNB specimens (for seamless pipes), or PRNB specimens produced from the same group of seam pipes. Regarding the stress concentrator shape, the advantages of the notched specimens in comparison with the pre-cracked ones are: they are significantly more convenient for fabrication, the notch represent a straight stress concentrator and results in a symmetric final crack front.

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References

Bergant, M., Yawny, A., Perez Ipiña, J., 2015. Numerical study of the applicability of the g-factor method to J-resistance curve determination of steam generator tubes using non-standard specimens. Engineering Fracture Mechanics 146, 109–120.

Dimić, I., Arsić, M., Medjo, B., Stefanović, A., Grabulov, V., Rakin, M., 2013. Effect of welded joint imperfection on the integrity of pipe elbows subjected to internal pressure. Technical Gazette 20, 285–291.

Dutta, B.K,. Saini, S., Arora N., 2005. Application of a modified damage potential to predict ductile crack initiation in welded pipes. International Journal of Pressure Vessels and Piping 82, 833–839.

Gajdos, L., Sperl, M., 2012. Evaluating the integrity of pressure pipelines by fracture mechanics. in *"Applied Fracture Mechanics"* In: Belov A. (Ed.). InTech, Rijeka, pp. 283.

Gubeljak, N., Vojvodić Tuma, J., Šuštaršić, B., Predan, J., Oblak, M., 2007. Assessment of the load-bearing capacity of a primary pipeline. Engineering Fracture Mechanics 74, 995–1005.

Gubeljak, N., Likeb, A., Matvienko, Y., 2014. Fracture toughness measurement by using pipe-ring specimens. Procedia Materials Science 3, 1934–1940.

Koo, J.M., Park, S., Seok, C.S., 2013. Evaluation of fracture toughness of nuclear piping using real pipe and tensile compact pipe specimens. Nuclear Engineering and Design 259, 198–204.

Kozak, D., Ivandić, Z., Konjatić, P., 2010. Determination of the critical pressure for a hot-water pipe with a corrosion defect. Materials and Technologies 44, 385–390.

Likeb, A., Gubeljak, N., Matvienko, Y., 2014. Finite element estimation of the plastic ηpl factors for pipe-ring notched bend specimen using the load separation method. Fatigue and Fracture of Engineering Materials and Structures 37, 1319–1329.

Likeb, A., 2014. Suitability of pipe-ring specimen for determination of fracture toughness. PhD Thesis, University of Maribor, Faculty of Mechanical Engineering, Slovenia (in Slovenian)

Mahajan, G., Saxena, S., Mohanty, A., 2016. Numerical characterization of compact pipe specimen for stretch zone width assessment. Fatigue and Fracture of Engineering Materials and Structures 39, 859–865.

Marenić, E., Tonković, Z., Skozrit, I., 2010. On the calculation of stress intensity factors and J-integrals using the submodeling technique. Journal of Pressure Vessel Technology – ASME 132, 041203.1–12.

Martić, I., Sedmak, A., Tomić, R., Hot, I., 2016. Remaining life determination for pressure vessel in a refinery. Structural Integrity and Life 16, 49–52.

Medjo, B., Rakin, M., Arsić, M., Šarkoćević, Ž., Zrilić, M., Putić, S., 2012. Determination of the load carrying capacity of damaged pipes using local approach to fracture. Materials Transactions - JIM (Japan Institute of Metals and Materials) 53, 185–190.

Medjo, B., Rakin, M., Gubeljak, N., Matvienko, Y., Arsić, M., Šarkoćević, Ž., Sedmak, A., 2015. Failure resistance of drilling rig casing pipes with an axial crack. Engineering Failure Analysis 58, 429–440.

Musraty, W., Medjo, B., Gubeljak, N., Likeb, A., Cvijović-Alagić, I., Sedmak, A., Rakin, M., 2017. Ductile fracture of pipe-ring notched bend specimens - micromechanical analysis. Engineering Fracture Mechanics 175, 247–261.

Sedmak, A., Algool, M., Kirin, S., Rakičević, B., Bakić, R., 2016. Industrial safety of pressure vessels - Structural integrity point of view. Chemical Industry 70, 685–694.

Xu, J., Zhang, Z.L., Østby, E., Nyhus, B., Sun, D.B., 2009. Effects of crack depth and specimen size on ductile crack growth of SENT and SENB specimens for fracture mechanics evaluation of pipeline steels. International Journal of Pressure Vessels and Piping 86, 787–797.

Xu, J., Zhang, Z.L., Østby, E., Nyhus, B., Sun, DB., 2010. Constraint effect on the ductile crack growth resistance of circumferentially cracked pipes. Engineering Fracture Mechanics 77, 671–684.

Zhang, Z.L., Thaulow, C., Odegard, J., 2000. A complete Gurson model approach for ductile fracture. Engineering Fracture Mechanics 67, 155–168.