Seam pipes for process industry – Fracture analysis by using ring-shaped specimens

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Abstract

Pipelines are commonly used in process industry for transport of fluids, as well as granular solids, due to their numerous advantages in comparison to other transportation means. Pipe integrity is essential for a reliable work of the entire plant, as well as for safety assurance. Also, serious ecological consequences may follow the pipeline failure in some cases, i.e. due to the leak of toxic, flammable or otherwise dangerous fluids in a chemical or some other plant. Therefore, it is very important to examine the fracture behaviour of pipelines, which is done here by testing the recently proposed ring-shaped specimens exposed to bending. The specimens were fabricated from a seam pipe for pressure applications (allowed for usage on temperatures up to 300 °C). Initial defects, very narrow notches, were machined either in the base metal and weld metal (seam) or in the base metal only. Regardless of the defect position, ductile fracture mechanism is observed in all specimens. The results show that the ring-shaped specimen can be successfully used for fracture characterisation of pipeline material, especially for thin-walled pipes which are not suitable for production of standard fracture mechanics specimens due to the insufficient wall thickness.

Keywords: *pipe failure, pipe ring notched bend specimens, ductile fracture*.

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Pipelines are used in the process industry for transportation of different fluids and granular solids. They are mounted in chemical and pharmaceutical plants, energetic facilities, food and beverage production plants, etc., as well as in fields, for large distance transportation. It can be said that pipelines are of strategic importance for the chemical industry; some of the good sides are: they are energy efficient, enable supply of materials and energents, but they are also safer than other transportation means.

Pipes can be produced from metallic or non-metallic materials, depending on the needs of particular industry. Metallic pipelines, which are topic of this work, consist of seamless or seam (welded) pipes. Modern technologies for production of seam pipes enable continuous production of longitudinal and spiral welded pipes; the latter are mostly produced in nominal diameters exceeding DN300 (*i.e.*, external diameters exceeding 323.9 mm). The main aim in production of seam pipes is achieving the welding speed equal to the forming speed. Unfortunately, the welded joints in pipes are typically prone to defects, just like in any other welded structure, caused by the welding procedure. Examples of such defects are lack of fusion, hot and cold cracks, etc.

Analysis of stress/strain state, fracture, integrity assessment and remaining service life of pipelines is an important topic for different industry branches. Some studies dealing with these issues on different process system elements (such as pipes, elbows, valves, vessels) are presented in literature [1–15]. Fracture of steels and other metallic materials under the action of static loading can generally be categorised as ductile [1,9] or brittle [14,16]. Mechanisms of damage and loss of load carrying capacity of pipeline components are different, and besides ductile/brittle fracture [1–5,9,10,14] and plastic collapse [2,6–8,11], they also include fatigue [17] and creep [18]. Additionally, phenomena like corrosion [11,19], erosion [20] and cavitation [21] can significantly influence the structural integrity.

In exploitation, it is rather important to be aware of possible initial defects, caused by production, thermomechanical treatment or assembly operations. Some of them can be prevented by selection and application of a proper pipe fabrication procedure, including suitable control operations. As mentioned before, an important

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source of initial defects is welding - either during production (axial or spiral welds on seam pipes) or joining the pipes (circumferential welded joints). Quality testing of the welded (seam) pipes is considered in [22].

Experimental fracture testing of the pipeline material is often difficult, because the standard requirements regarding the specimen/crack geometry cannot be fulfilled for all wall thicknesses. Examples of these specimens are SENB (single-edge notched bending) and CT (compact tension), according to ASTM E1820 standard [23]. Therefore, some authors have previously proposed other test specimens. In literature [5,24], the advantages of the SENT specimen (single-edge notched tension, [25]) over standard SENB specimen are discussed for configurations with a circumferential crack in pipelines exposed to axial loading. For this defect position, there are also some other proposals, e.g. compact pipe specimens [26,27].

However, the main focus in this work is testing the fracture behaviour of the thin-walled pipes with a defect in the other direction – axial, exposed to internal pressure. Specimen type used for this purpose is recently proposed as pipe ring notched bending specimen (PRNB) [28–32]. Regarding the axial defect position, which is critical in cylindrical geometries exposed to internal pressure, there are also some other proposed non-standard specimens (besides PRNB), such as curved compact tension (CCT) specimens [33], or several other configurations [34]. Unfortunately, all of the mentioned configurations require complex preparation or complex testing setup, tools, etc.

SPECIMENS AND TESTING

PRNB specimen geometry is shown in Figure 1; the stress concentrator marked in the figure can generally be a machined notch (used in this work) or a fatigue pre-crack.

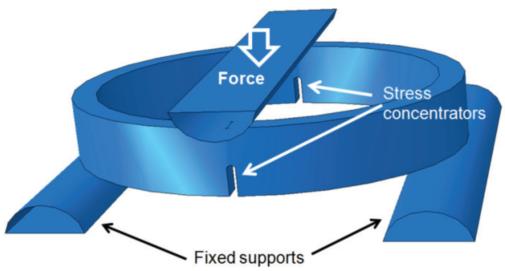

Figure 1. PRNB specimen. Reprinted with permission from [31], Copyright by Elsevier, 2017.

In previous studies [28–31] we have mainly focused on preparation and examination of the new specimen shape based on the ring geometry. The specimens were cut from bulk steel/plates, and verified against the standard SENB specimen, which has similar character of loading and stress concentrator geometry as PRNB specimen. The specimens cut from the plates were characterized by much thicker walls (ratio of the external to the internal diameter was around 1.13) in comparison with the ones examined in this work (ratio of the external to the internal diameter is around 1.04, the specimens are cut from seam pipes).

Fracture mechanics parameters are considered previously [29], as well as calculation of *J* integral for these geometries [28]. Also, for the purpose of verification against a standard specimen, fracture behaviours of PRNB and SENB specimen were compared [29,30,35]. The aim was to develop a new specimen geometry, which would be convenient, but also verified for practical application (primarily because of its shape), having in mind limitations of standard specimens in determining the fracture behaviour of pipelines.

In this work, fracture of PRNB specimens with thin walls, cut from seam pipes, is analysed. Stereometric measurement is used to assess the strain field, as well as fracture mechanics parameters (CMOD and CTOD – crack mouth/tip opening displacement).

The pipe material is a non-alloy steel tube for pressure purposes – grade P235TR1 (according to EN 10216-1 standard); chemical composition of the material is shown in Table 1, while tensile properties are: yield strength 328 MPa, tensile strength 420 MPa and elongation at fracture 38%. These are the values from the manufacturer's inspection certificate for the considered pipes.

Table 1. Chemical composition of the pipe material, wt.% [36]

C	Mn	Si	S	P	Al
0.13	0.54	0.02	0.012	0.01	0.052

Dimensions of the specimens are shown in Figure 2 and Table 2; Figure 2 shows the seam pipe and a specimen cut from it, along with the testing scheme (three point bending). Ring external or outside diameter is denoted as D_o, specimen width as W, thickness as B, while initial defect (in this case, machined notch) length is marked as a. The examined specimens were notched, and notch radius was 0.25 mm. Stable crack growth by ductile fracture mechanism is observed in all of them. It was discussed previously [29] that machined notches, such as those fabricated by electrical discharge machining (EDM), can produce reliable and repeatable results as initial defects. Therefore, it is decided not to form the fatigue pre-cracks, mainly due to the fact that the fatigue crack growth leads to an uneven shape of the pre-crack along the crack front (crack is longer on the internal surface than on the external one) [29,32].

Table 2 presents measured values of the external diameter D_o and wall thickness B. Nominal external diameter for all specimens is 168.3 mm, while the

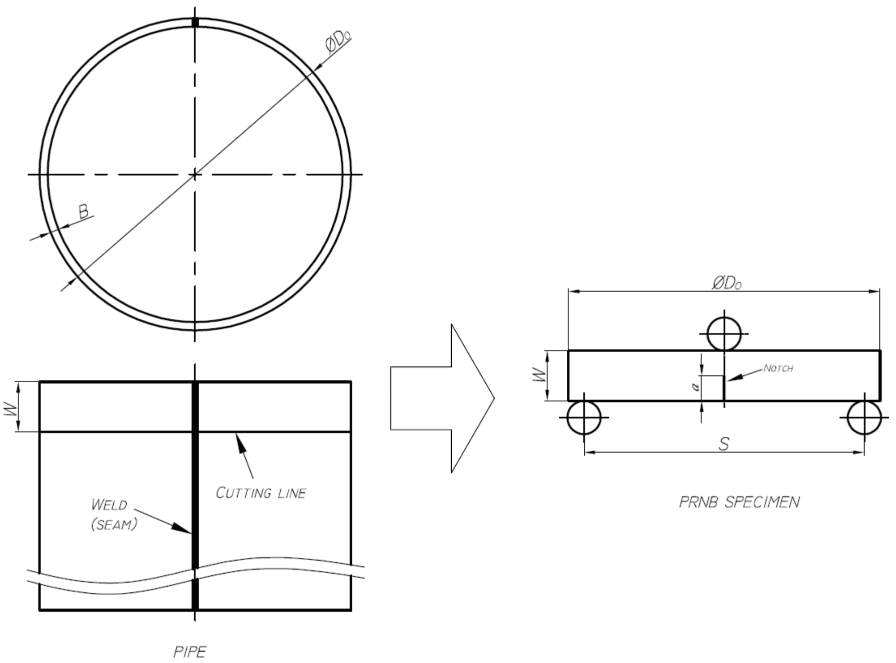

Figure 2. Pipe and specimen geometry with testing scheme.

nominal wall thickness is 3.2 mm (for specimens 3, 8 and 43) and 3.5 mm (for specimen 7). These values are shown in diagrams in section 3.

Ratio of the specimen width to wall thickness, *W*/*B*, is either 4 or 6, as shown in Table 2. This value is varied in order to determine its influence on fracture resistance of the pipe ring specimens.

During testing under the action of static loading, strains on the specimen surface are monitored using the stereometric measurement system, Figure 3. Displacement of surface points is measured using two connected cameras. In order to enable this procedure, the surface is sprayed with a contrasting colour (combination of black and white is the most often used) before testing. This leads to a "discretised" surface, and the software package, in this case GOM Aramis [37], can track the points with the increase of loading to determine their displacement, and subsequently calculate strains and other related mechanical quantities. For example, Figure 3 shows a view of the strain field obtained during testing of a specimen.

Advantages of stereometric measurements come into focus when heterogeneous materials, stress concentrators, small specimens and plastically deformed structures are tested. In this work, two fracture mechanics parameters (CMOD and CTOD, determined as δ_5) are determined using the displacement field recorded by Aramis software, i.e. by tracking the two appropriate sets of points at the positions near the crack tip (2.5 mm on each side of the tip) and crack mouth, as shown in Figure 3. An overview of use of the stereometric measurement in structural integrity assessment is shown in literature [38].

Contactless stereometric measurement is here applied under laboratory conditions. However, it can also be used during production or exploitation of a component or assembly, enabling the deformation tracking while the component is being produced or exposed to real-life loading scenarios. Some more details about the stereometric measurement in industry can be found in literature [37,39]. Of course, the entire equipment needs to be specially prepared for

Table 2. Dimensions of specimens for seam (notches in WM and BM)

Parameter	Pipe type			
	PRNB 3	PRNB 7	PRNB 8	PRNB 43
D_o / mm	168.18	168.43	168.21	168.28
B / mm	3.21	3.46	3.24	3.23
W / mm	12.99	21.05	19.26	19.23
W/B	≈ 4	≈ 6	≈ 6	≈ 6
a/W (notch radius = 0.25 mm)	0.5	0.5	0.5	0.5
S = 0.9 D_o, in accordance with standard [23]	151.5	151.5	151.5	151.5

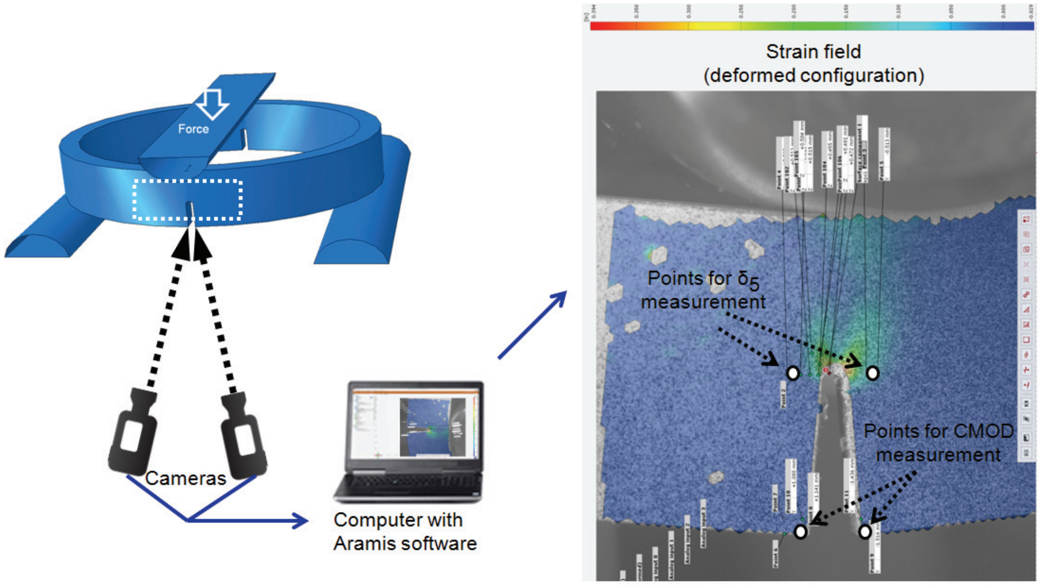

Figure 3. Stereometric system GOM Aramis with two cameras and software for image analysis - schematic view

such application, including the selection of appropriate data acquisition and transfer systems.

RESULTS AND DISCUSSION

As described previously, ductile fracture of PRNB specimens is examined by using a tensile testing machine, including the appropriate fixtures for bending. One side of the specimen was monitored by Aramis stereometric measurement system, while a COD gauge was mounted on the other side (*i.e.*, other notch). For rings with a notch positioned in the seam, the side with the seam is monitored using the Aramis system.

After the static testing, the specimens were cooled in liquid nitrogen, and broken into two parts, in order to obtain the shape and size of ductile fracture surfaces. Fractured specimen PRNB8 is shown in Figure 4. The crack growth (initial and final crack fronts) is highlighted on both fracture surfaces. It can be seen that the crack growth is much more pronounced in the weld metal than in the base metal.

The difference in crack resistance between the weld metal and the base metal can be seen in Figure 5, where final crack lengths for all specimens are shown. For each of them, the length of the crack in the seam is significantly larger than the crack length in the base metal. It can be seen that the trends for all three specimens are very similar. An extreme case is observed for specimen PRNB 3, where the crack in the base metal did not grow at all.

The force – CMOD (crack mouth opening displacement) curves for PRNB specimens 3, 7 and 8 are shown in Figure 6. Two curves are presented for each specimen, since two CMOD values are measured – the first using data from the stereometric measurement system and the second from the COD gauge on the other side. The values are different, which may be caused by differences in material properties; the notch on one side is in the weld metal, while the notch on the other side is in the base metal.

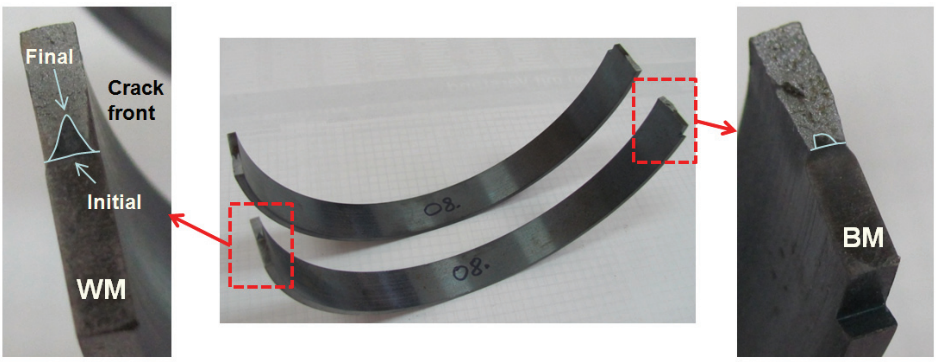

Figure 4. Fractured ring specimen PRNB8, with enlarged view of fracture surfaces in the welded joint (seam) (WM) and base metal (BM).

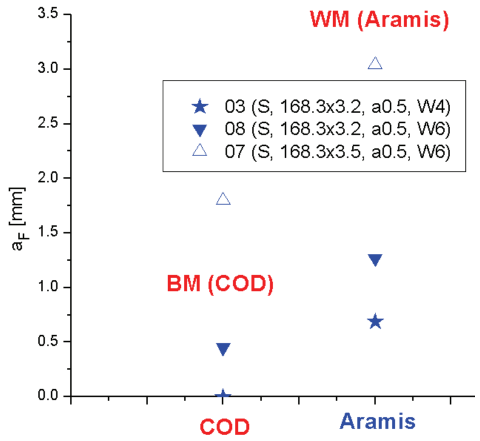

Figure 5. Crack growth in the seam and base metal.

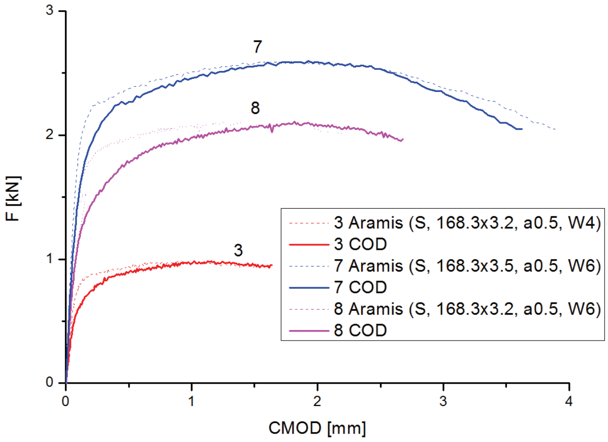

Figure 6. F-CMOD curves for PRNB specimens with a notch in the seam.

Diagram in Figure 7 shows crack growth resistance curves for specimens with a notch in the seam. CTOD (crack tip opening displacement), obtained here using δ_5 concept [40], is used as a fracture mechanics parameter. Its values are obtained using the stereometric measurement, while crack growth data are determined based on the fracture surface analysis (initial and final crack length measurements, a_0 and a_F) and normalization procedure in accordance with the standard ASTM E1820 [23,41].

The crack growth is determined using the ESIS (European Society for Structural Integrity) P2-92 procedure [42], by measurements along nine parallel lines on fractured surfaces. The original and final crack lengths, a_0 and a_f, respectively, are determined using the expression:

$$a = \frac{1}{8}\left\{\frac{a_1 + a_9}{2} + \sum_{i=2}^{8} a_i\right\} \qquad (1)$$

The crack growth is calculated as: $\Delta a = a_f - a_0$.

It can be seen that fracture resistance curves CTOD-Δa, shown in Figure 7, exhibit very similar trends, despite the difference in the final crack growth (*i.e.*, the moment when the experiment was stopped). Also, it should be noticed that the change of pipe wall thickness (from 3.2 to 3.5 mm) or ratio W/B (4 and 6) has not significantly influenced the results.

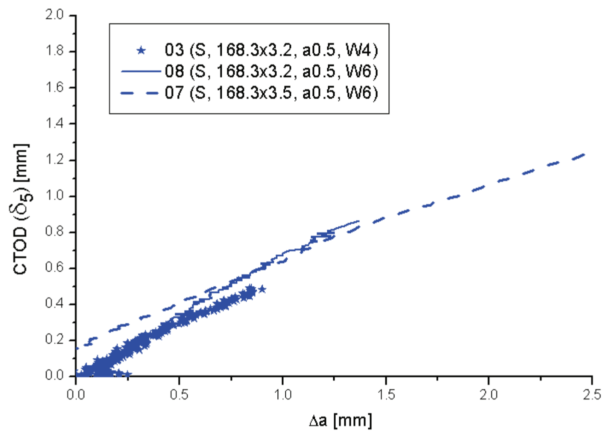

Figure 7. Crack growth curves - initial defect in the seam.

The difference between the crack growth resistance of the weld metal (seam) and the base metal can be seen in Figure 8. A specimen (PRNB 43) with both notches in the base metal is added to the previously shown results. The fracture resistance of the base metal is higher in comparison with the seam. This is in agreement with the data obtained by the crack length measurement, Figure 5, where seam crack was longer than the crack through the base metal for each of the examined specimens.

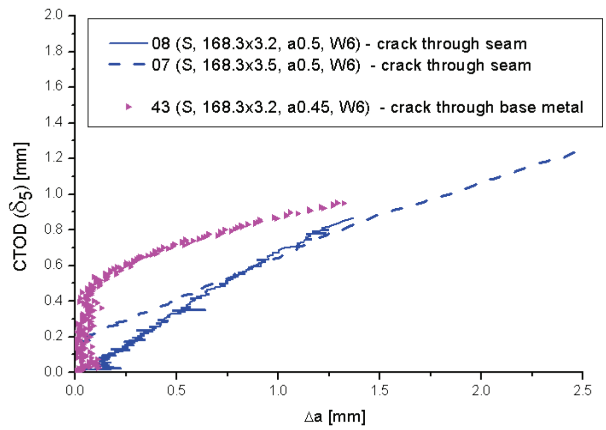

Figure 8. Crack growth curves - initial defect in the seam and in the base metal.

Unlike the previously published work, these results are obtained by testing the thin-walled seam pipes ($D_o/D_i \approx 1.04$). As mentioned previously, they can be especially problematic when testing of standard fracture mechanics specimens is considered. In other words, sufficient thickness for standard testing may not be possible to achieve.

CONCLUSIONS

Recently proposed pipe ring notched bend (PRNB) specimens for determining the fracture resistance of ring-shaped geometries are applied in experimental fracture analysis of seam pipes, commonly used for pressure applications in chemical plants and energy facilities. Initial defects in the pipeline material (machined notches) were positioned in the seam and in the base metal. A stereometric optical measurement system is applied for determining strain development on the specimen surface. Also, it is applied for obtaining the fracture parameters, CMOD and CTOD. It can be concluded that the seam exhibits lower fracture resistance in comparison to the base metal, based on the crack growth resistance curves and fracture surfaces. Also, the crack growth resistance curves of the specimens with the initial defect in the seam are not significantly influenced by the increase of wall thickness (approx. 10%) or change of ratio of specimen width and thickness. Therefore, it can be said that the pipe-ring notch bend specimens can be reliably applied in engineering practice. Future work will include further validation on different pipeline materials and broader range of pipe diameters/wall thicknesses, with the aim to generalize and standardize the proposed testing procedure.

Acknowledgement

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IZVOD

ŠAVNE CEVI ZA PROCESNU INDUSTRIJU – ANALIZA LOMA PRIMENOM EPRUVETA OBLIKA PRSTENA

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(Naučni rad)

Cevovodi su često korišćen vid transporta fluida i čvrstih materijala u obliku granula u procesnoj industriji, zbog svojih brojnih prednosti u poređenju sa drugim načinima transporta. Njihov integritet je veoma važan za pouzdan i bezbedan rad celog postrojenja. Takođe, ozbiljne ekološke posledice mogu biti izazvane otkazom cevovoda u nekim slučajevima, npr. zbog curenja otrovnih, zapaljivih ili na drugi način opasnih fluida u hemijskim i drugim postrojenjima. Stoga, veoma je važno ispitati ponašanje cevi pri lomu, što je u ovom radu urađeno korišćenjem epruveta oblika prstena izloženih savijanju, kao nestandardnih epruveta predloženih u prethodnom periodu. Epruvete su izrađene od šavnih cevi za primenu pod dejstvom unutrašnjeg pritiska (na temperaturama do 300 °C). Početna oštećenja, zarezi veoma male širine, su izrađena ili u metalu šava i osnovnom metalu, ili samo u osnovnom metalu. Nezavisno od položaja početnog oštećenja, mehanizam žilavog loma je uočen kod svih epruveta. Rezultati pokazuju da se epruvete oblika prstena mogu uspešno koristiti za karakterizaciju loma materijala cevovoda, posebno za tankozidne cevi koje nisu pogodne za izradu standardnih epruveta mehanike loma zbog nedovoljne debljine zida.

Ključne reči: Lom cevi • Šavne cevi • Analiza loma