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Additively manufactured tensile ring-shaped specimens for pipeline material fracture examination - influence of geometry

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Abstract

In order to define a procedure for integrity assessment of pipelines and determining the fracture mechanics parameters, a new type of specimen with a sharp notch, Pipe Ring Notched Tension (PRNT) specimen, is tested. The aim of the study is to determine the influence of the specimen geometry (cylindrical shape, as well as number and length of stress concentrators) on parameters such as force, Crack Mouth Opening Displacement CMOD, Crack Tip Opening Displacement CTOD and J integral. The specimens were fabricated by an additive production method - selective laser sintering (SLS). EOS Formiga P100 machine is used, and the material is polyamide PA12. In addition to Pipe Ring Notched Tension specimens, Single Edge Notched Tension (SENT) specimens with identical cross section were also considered. All specimens were tested on a universal tensile testing machine. A tool specially designed to apply contact pressure to the inner walls in the tension direction was used, simulating the internal pressure. For determining the field of displacement and strain on the surface of the tested samples that occur during the loading, Aramis GOM 2M optical measurement system was used. Aramis is applied for determination of geometry fracture mechanics parameters: CMOD and CTOD (based on δ_5 concept). In addition to the examination of fracture properties of additively manufactured PA12, the main topic of this work is the development of the non-standard testing procedure, which will be subsequently applied to the specimens cut from metallic or non-metallic pipes. As an important part of this procedure, the calculation of fracture parameters will be conducted based on the results presented here.

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Keywords: *PRNT; Additive manufacturing; Fracture mechanics;*

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1. Introduction

Cracks are threat to pipeline structural integrity, as is the case for all other types of pressurized equipment. Focus is always on welded joints due to their sensitivity to cracks and their stable or unstable growth, Amara et al. (2018), Jovanovic et al. (2020), Medjo et al. (2020), Jeremic et al. (2020), Kirin et al. (2020), Jeremic er al. (2021), Aradjelovic et al. (2021), Aradjelovic et al. (2021), Milovanovic et al. (2021), Zaidi et al. (2022), although defects can also occur in the base material. Thus, defects and damage that occurs in-service must be understood and controlled, to ensure structural integrity of pipelines, be it with a small diameter to collect the product (e.g. crude oil, liquefied petroleum products) from where it is extracted, or with large diameter pipeline which transports the product to refineries.

In order to enable safe and efficient exploitation of pressurized pipelines, different aspects of the pipeline behavior exposed to loading have to be analysed and understood. One of them is deformation and failure of the pipeline in the presence of an initial defect, which can be volumetric or sharp. Depending on the defect type and size, they can significantly influence the integrity of the pipes and other pipeline elements, and decrease the working life. Having in mind possible consequences which can arise from the pipeline failure, especially those for transportation of flammable, explosive, toxic or otherwise dangerous fluids, this is a topic which gains a lot of attention recently.

The pipes fabricated by conventional production methods are often categorized as seam and seamless ones. The sizes which are used in different applications belong to a very wide range; for example standard EN 10216-2 defines over 950 different dimensions (diameter / wall thickness). In addition to different sizes, the pipes can be fabricated from different materials, either metallic or non-metallic. However, most of the pipelines have a common problem when it comes to fracture resistance testing, i.e. it is not convenient or even possible to apply the standard procedures, such as Standard Test Method for Measurement of Fracture Toughness ASTM E1820. The main reason is insufficient thickness of the pipe for obtaining the standard fracture mechanics specimens, such as SENB (Single Edge Notched Bending) (Fig. 1), CT (Compact Tension) and DCT (Disk-Shaped Compact) defined by the standard ASTM E1820. Similar or same geometries are defined by other standards, as well. The limiting factor, especially for the thin-walled pipes, is the thickness B (shown in Fig. 1 for SENB specimen), Zhu et al. (2015).

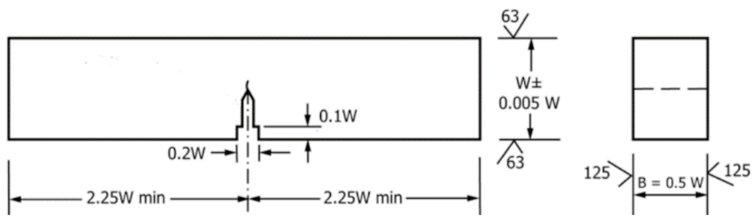

Fig. 1 Recommended Single Edge Notched Bending Specimen, [2]

Having in mind that the majority of the pipelines in different industry branches are thin-walled, different proposals can be found in the literature for their fracture assessment. Defining the non-standard testing procedures for this purpose is a topic dealt by several research groups, with a common aim to determine the fracture resistance of pipelines in laboratory conditions (i.e. on laboratory specimens), in a manner which will adequately emulate the exploitation conditions. Most of such studies are published in the last 10 years, Gajdos et al. (2012), Zhang et al. (2015), Mahajan et al. (2016), Kiraly et al. (2018), Gurovich et al. (2020), Bianchetti et al. (2021).

It can be said that the basis for development of the new Pipe Ring Tension (PRNT) and the procedure for its testing is the work on the Pipe Ring Notch Bending (PRNB) specimen geometry, initiated by N. Gubeljak and Y. Matvienko, Gubeljak et al. (2014), and further developed through experimental and numerical analyses of failure conditions of these specimens, Medjo et al. (2015), Musraty et al. (2017), Damjanovic et al. (2019).

The main aim of this work is introduction of a new testing procedure, which uses the same or similar geometry as PRNB specimen, but exposed to tensile loading on the internal surface of the ring specimen, as opposed to bending load acting on PRNB specimen. The tests are performed on the additively manufactured specimens, and the (initial) results of these tests presented here will be the basis for development of the fracture mechanics parameters calculation procedure for different geometries of PRNT specimens.

Nomenclature

a_0	Sharp notch initial length [mm]
a	Sharp notch length [mm]
D	Ring diameter [mm]
B	Wall thickness [mm]
W	Specimen width
PRNT	Pipe Ring Notch Tension specimen
SENT	Single Edge Toch Tension specimen
SLS	Selective Laser Sintering

2. Materials and Methods

For the purpose of development of the new fracture assessment procedure for testing of pipeline materials, the specimens (PRNT, Fig. 2) fabricated by EOS Formiga P100 machine are tested. The fabrication technique was SLS (*selective laser sintering*), an additive manufacturing technique. The specimens are made from polyamide powder PA12, and the layers are stacked in the planes perpendicular to the ring axis.

Fig. 2 PRNT specimens fabricated from PA12 material.

The specimens have different ratios of the initial sharp notch length and specimen width; they are marked as PRNT-S (a = 3.2 mm) and PRNT-L (a = 4.6 mm). Experimental testing is conducted on Shimadzu AGS-X universal testing machine, with capacity up to 100kN. Having in mind the cylindrical geometry of the specimen, a specially designed tools are used for transferring of the tensile loading from the machine to the internal surface of the rings. During the testing, the surface deformation of the specimen is monitored by the digital image correlation (DIC) system Aramis GOM 2M. Tensile testing is performed in displacement control, and Aramis DIC system recorded stages with results with the interval of 2 seconds. In addition to the experimental testing, numerical models of the specimens are formed. Numerical analysis is performed in the software package Simulia Abaqus; crack growth is not considered, i.e. stress fields and fracture mechanics parameters are determined in stationary conditions.

3. Results

3.1. Experimental results

By examining the ring-shaped (PRNT) specimens, the dependence of the force on CMOD is recorded for different initial defect length, Fig. 3. The specimen with the longer initial defect is denoted as PRNT-L, and the one with shorter defect is PRNT-S. The force values are obtained from the tensile testing machine, while CMOD is tracked by the digital image correlation system.

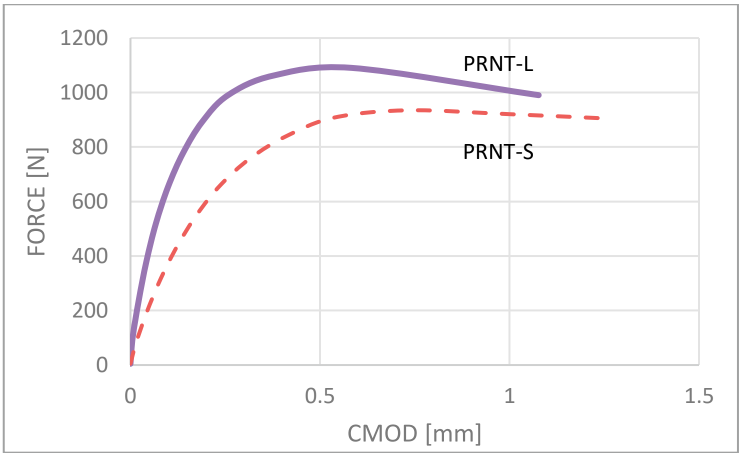

Fig. 3 Diagram of force dependence on CMOD - Representative samples.

Fig. 4 presents an example of a report from Gom Aramis software for strain measurement; as mentioned previously, the values of CMOD from the previous figure are obtained this way, by extracting the change of positions of the points at the crack mouth during the loading increase. The report in Fig. 4 gives different ways for visualization of the equivalent stress fields, either by full field view or through diagrams obtained along pre-defined lines in the highly deformed area.

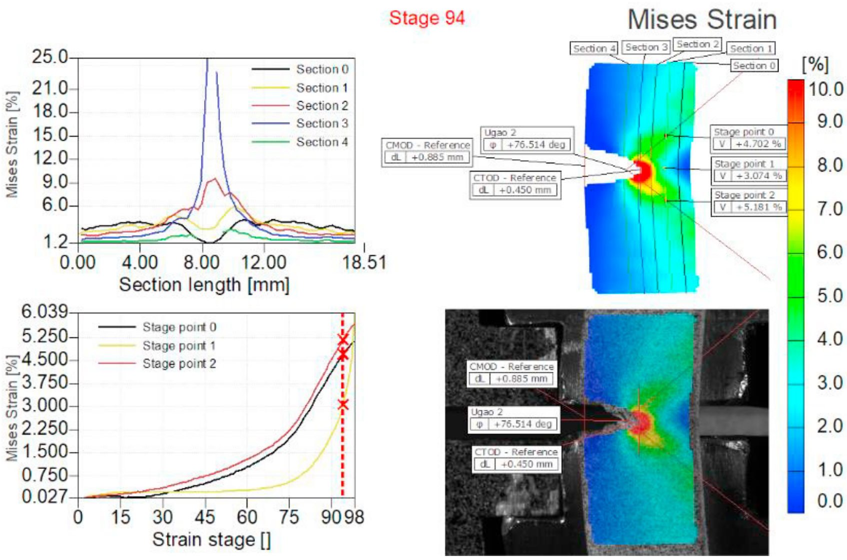

Fig. 4 Report from Gom Aramis – equivalent strain field at the surface of the specimen.

3.2. Numerical results

Finite element method is applied for determination of strain and stress fields, as well as calculation of the fracture mechanics parameters (in this work, J integral is shown). Fig. 5 shows the deformed specimen with the maximum principal strain field; having in mind the symmetry of the specimen only one half is modeled, with the introduction of the symmetry boundary conditions. In the same figure, surface domain for calculation of the J integral is marked.

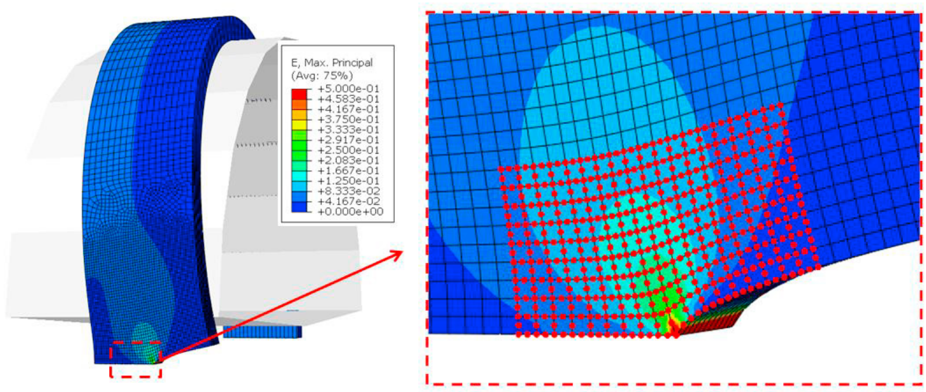

Fig. 5 PRNT model – maximum principal strain field and surface domain for *J* integral calculation

The values of the *J* integral are obtained from the numerical models, by application of the domain integral technique. *J* integral is extracted from the model in order to calculate the values of the stress intensity factors and determination of the ratio of maximum values for PRNT and SENT specimen for different dimensions of the specimens and initial defects. Fig. 6 shows a comparison between the values of the *J* integral along the crack front for PRNT and SENT specimen. It can be seen that the SENT specimen gives a symmetrical distribution, while asymmetry caused by the cylindrical geometry exists in the case of PRNT specimen.

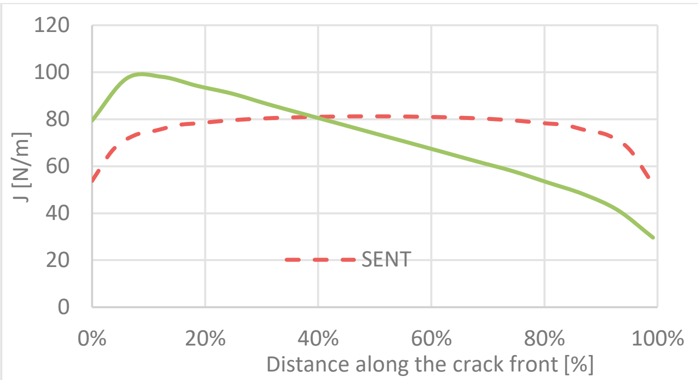

Fig. 6 Values of the *J* integral on the path for the PRNT-L and SENT-L model.

Presented initial results obtained by experimental and numerical examination of the ring specimens will be used in development of a non-standard testing procedure for fracture assessment of the pipeline materials fabricated from different materials. One of the goals is to propose the expressions for calculation of the energy-based fracture mechanics parameters - stress intensity factor *K* and *J* integral, for a wide range of the pipe sizes.

4. Conclusion

In this work, two specimen geometries with initial defects, fabricated from PA12 polymer by selective laser sintering, are examined. One of these specimens is a new geometry, pipe ring notch tension (PRNT) specimen, which is being developed for determination of fracture resistance of the pipeline walled pipes. The experimental examination included tracking of the surface deformations by application of a digital image correlation system. This enabled the formation of the force - CMOD curves for the specimens, where CMOD, crack mouth opening displacement, is obtained from DIC measurement. The influence of the change in the stress concentrator length is determined. Numerical analysis enabled the determination of the stress and strain fields for the stationary pre-cracks, and also the values of the *J* integral, as energy-based fracture mechanics parameter. The values of the *J* integral are tracked along the crack tip, and it is determined that the PRNT specimen is characterized by higher maximum value, while the SENT specimen has a symmetric distribution along the front. This difference will be a basis for further analysis of the influence of the cylindrical geometry on the values of the fracture mechanics parameters, aimed at determination of the stress intensity factor for PRNT specimen by using the SENT specimen as the basis for calculation.

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