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Proposal of new Pipe-Ring specimen for fracture mechanics

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Abstract

Thin - walled pipes are not suitable for measuring fracture toughness parameters which are of vital importance in pipes because the crack failure is the most common in pipes. They are not suitable because it is impossible to make standard specimens for measuring the fracture toughness like SENB or CT specimens from the thin wall of the pipe. Lot of researches noticed this problem, but only few are found the good and cheap alternative solution for measuring the fracture toughness. Gubeljak and Matvienko proposed so - called Pipe - Ring specimen (PRS) or Pipe - Ring Notched Bend specimen (PRNB) as alternative solution to the SENB specimen. Until now, only the idealized geometry of PRS specimen is analysed, so specimen which is not cut out from the real pipe but made from plate. On this way, the residual stresses are neglected. The aim of this work is to estimate the hoop residual stresses in the real pipes used in boiler industry, produced by hot - rolling technique, so seamless pipes. These kinds of pipes are delivered only normalized, but not stress relieved too. Therefore, there are surly residual stresses present in pipes which are result of manufacturing technique, but also of uneven cooling after the production process. Within this work, hoop stress as the most relevant for pipes is estimated by two methods: incremental hole drilling method and splitting method. Although residual stresses are cause of collapse of many constructions, still in most cases of analysis and design of individual parts, structures and plants residual stresses are not taken into consideration. Residual stresses surly have some effect on the fatigue behaviour of materials as well as on the fracture toughness of material, therefore it is recommended to take them into account while calculating the lifetime of component or structure.

Keywords: residual stress; pipe; hoop stress; incremental hole drilling method; splitting method; tensile test; F - CMOD; PRS; PRNB; SENB

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1. Introduction

Within this work, residual stresses are estimated in PRS specimens who are cut out from the real pipe, and the basic idea is that one PRS specimen loaded with double force in relation to the SENB specimen has very similar behavior, Figure 1. This kind of specimen is proposed by Matvienko and Gubeljak as replacement for standard Single Edge Notched Bend specimens (SENB) for measuring the fracture toughness of material [1], [2], [3], [4], [5]. Since in most cases of thin walled pipes it is impossible to produce the standard SENB specimen from pipe wall, PRS specimen is the simplest and the cheapest alternative solution. On example of pipes considered in this researches, seamless pipes produced according to the EN 10216-2, there are 951 different pipe dimension available, but only from 251 pipes it is possible to produce standard SENB specimen, and from 700 pipes it is not possible due to thin wall of the pipe or due to the small outside diameter.

In [6] Likeb was analyzed PRS specimens in relation to the SENB and Compact Tension (CT) specimens, but in order to avoid the residual stresses, PRS specimens are made from steel plate. So it is necessary to estimate residual stresses in pipes in order to assess their impact to the fracture toughness. Of course, residual stresses firstly depends on the production process of pipes, so besides of hot rolled pipes analyzed in this paper, it is necessary to estimate residual stresses also on other pipe types.

Since the residual stress are depend also on the dimensions of pipes, within this paper, residual stresses are measured on four different pipe dimensions varying the outside diameter and wall thickness as follows: D = 114,3 mm, B = 12,5 mm; D = 219,1

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mm, B = 22,2 mm; D = 168,3 mm, B = 8 mm and D = 193,7 mm, B = 7,1 mm. All considered pipes are made from standard boiler steel 16Mo3 according to the standard EN 10216-2.

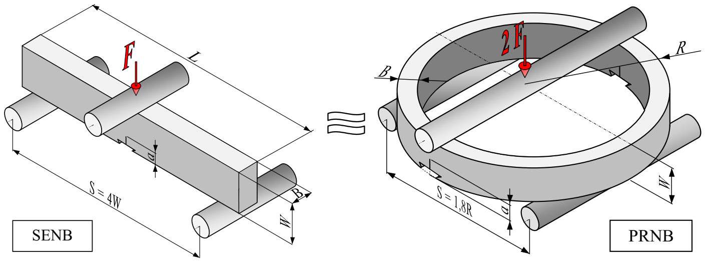


Fig.1 Similarity of SENB and PRS specimen

2. Experimental procedure

Since it is quite hard to simulate all the production process numerically, the residual stresses are estimated experimentally using two methods: incremental hole drilling method according to ASTM E 837-08 [7] and splitting method according to ASTM E 1928-99 [8].

For implementation of both methods, material properties are obtained from the tensile tests. Tensile specimens are made from all four considered pipe dimensions taking into account two states: as delivered state and stress relieved state in order to minimize the residual stresses.

Also in the previous researches about the PRS specimens, the imperfections of the pipes are neglected. According to the EN 10216-2 [9], tolerance for outside diameter of pipe is ± 1% or ± 0,5 mm (larger values is relevant) and tolerance for wall thickness is ± 12,5% or ± 0,4 mm (larger values is relevant). By performed dimensional analysis of considered specimens it is concluded that there are even larger deviations for wall thickness in some specimens, even for 9 % larger than allowable by standard. Since the dimensions of specimens can vary significantly, it is expected some deviation in the values of residual stresses as well.

2.1. Tensile test

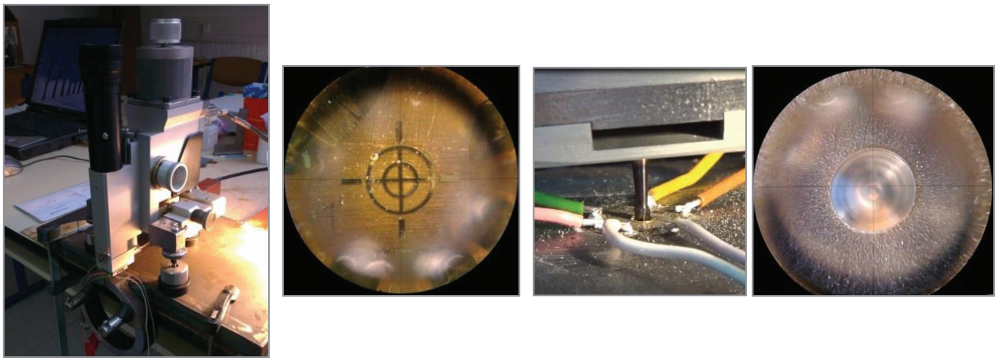
The actual characteristics of the material in means of E and ν are required for both: incremental hole drilling method and splitting method. So tensile tests are performed for specimens made from all four analyzed pipes in both states: as delivered and stress relieved state. Tensile specimens are made according to the DIN 50125:2004-01 [10] from the blank piece cut out in the longitudinal direction of pipe. From pipes with B = 12,5 mm and B = 22,2 mm tensile specimens with diameter d = 5 mm are made and from pipes with B = 7,1 mm and B = 8 mm tensile specimens with diameter d = 4 mm are made. 24 tensile specimens in total are made, 3 from every pipe in both mentioned states. Tensile tests are performed on the tensile testing machine Instron 1255-8500 Plus at the Fakulteta za Strojništvo in Maribor, Figure 2. E is obtained based on tensile tests, and ν is taken into account with value 0,3.


a) b) c)

Fig.2 Tensile test: a) tensile testing machine, b) tensile specimen with extensometer before testing, c) tensile specimen after testing

2.2. Incremental hole drilling method

Incremental hole drilling method (IHDM) is categorized as semi - destructive method since it implies drilling the small diameter hole (d = 1,8 mm) into the material and measuring the deformation around the hole using the special developed strain gauges called strain gauge rosette. This method is one of most widely used for fast and reliable estimation of residual stress field in components. This method is practically used to estimate residual stresses near the surface of component. Mathematical background for this method can be found in [11]. Figure 3 shows the MTS3000 device for measuring and some steps while measuring.



a) b) c) d)

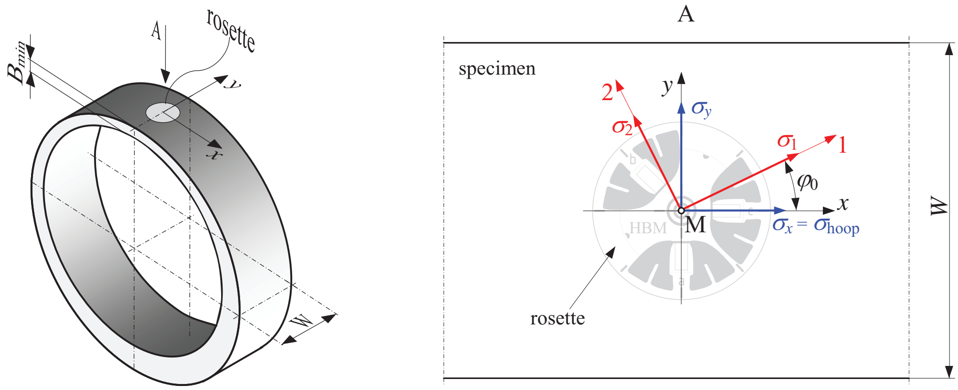
Fig.3 Measuring residual stresses using IHDM: a) MTS3000 device, b) rosette before hole drilling, c) drilling hole during measuring, d) drilled hole after measuring

Final results of IHDM method are values of principal stresses with their orientation. ($\sigma_1 = \sigma_{\max}$, $\sigma_2 = \sigma_{\min}$ and φ_0), Figure 4. As the hoop stress is the most relevant in pipes, those principal stresses are transformed to the basic coordinate system x - y using the equations (1) i (2) [12], Figure 4.

$$\sigma_x = \sigma_{\text{hoop}} = \sigma_1 \cos^2 \varphi_0 + \sigma_2 \sin^2 \varphi_0 \qquad (1)$$

$$\sigma_y = \sigma_1 \sin^2 \varphi_0 + \sigma_2 \cos^2 \varphi_0 \qquad (2)$$

According to (1), stress in x axes is hoop stress in pipe σ_{hoop}.



a) b)

Fig.4 Location of rosette and representation of stresses in basic x - y and main 1 - 2 coordinate systems

2.3. Splitting method

Quantitative estimation of residual stresses in pipes can be determined by cutting the pipe segment longitudinally and analyzing the change of outer diameter. Hatfield and Thirkell presented the idea firstly, and then Sachs and Espey [13] are modified it and come up with a simple method to calculate the approximate hoop stresses due to change in outside diameter of thin - walled pipes. This method implies linear stress distribution through the thickness of the pipe wall, which is acceptable in thin - walled pipes, Figure 5.

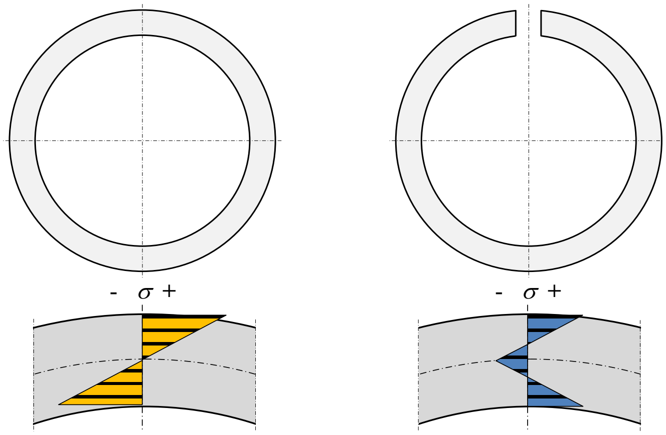


Fig.5 Schematic of the hoop residual stress distribution in rings manufactured from pipe before and after slitting [14]

The method is primarily used for pipes with outer diameter $D = 19 \div 25$ mm and wall thickness $B \leq 1{,}3$ mm, but there are no restrictions on the applicability of the method on other dimensions of pipes [8]. According to [8], hoop stress in pipe can be calculated as follows:

$$\sigma = \pm \frac{E \cdot B}{1-\nu^2} \cdot \frac{D_\mathrm{f} - D_0}{D_\mathrm{f} \cdot D_0} \qquad (2)$$

- where σ - hoop stress, MPa

E - Young's modulus of elasticity, MPa
B - effective wall thickness opposite of cut, mm
ν - Poisson's ratio, -
D_f - mean outside diameter of pipe after splitting, mm
D_0 - mean outside diameter of pipe before splitting, mm

Example of splitting ring method in case of some specimens is shown on Figure 6 and results for all specimens are presented in Figure 7 for both methods used. It is obvious much larger opening of slit in case of specimens with smaller wall thickness B and thus smaller specimen width W ($W = 2 \cdot B$). Also it is obvious a good effect of stress relieving, because the slit opening is much smaller in case of stress relieved specimens (those with sign "o" in specimen designation).

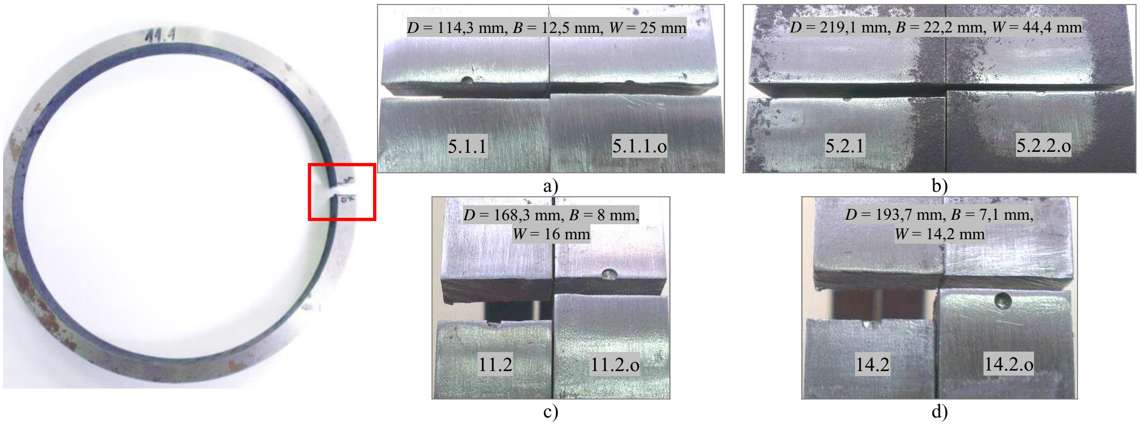


Fig.6 Example of splitting ring method on some specimens

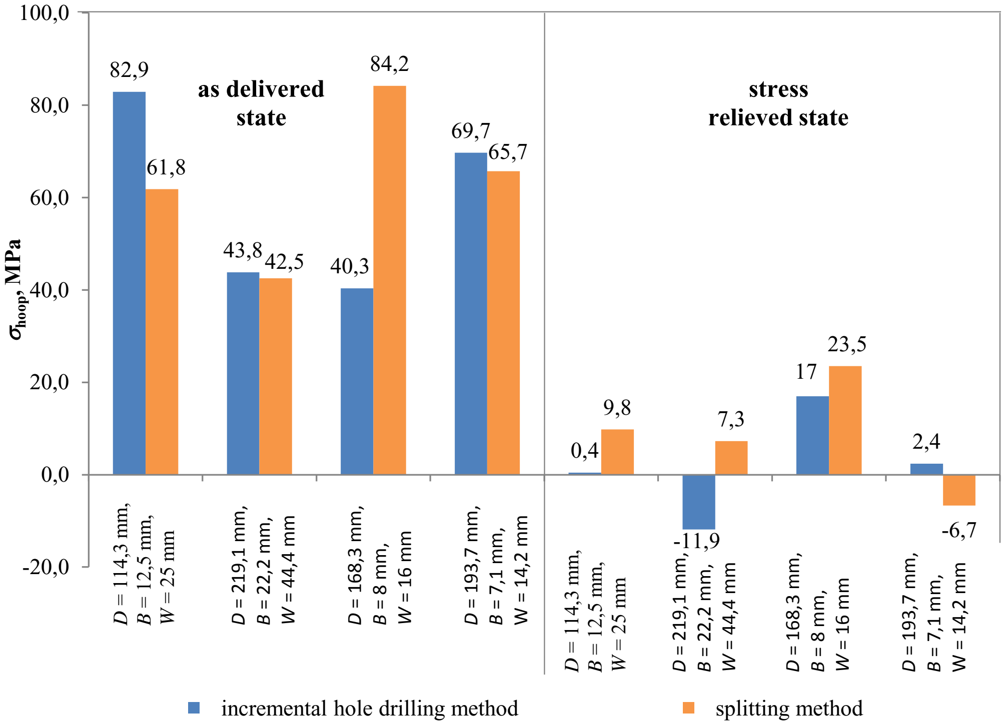


Fig.7 Final results of residual hoop stresses using both methods

2.4. Three point bend test of PRS specimens

In some previous researches about the PRS specimens it is concluded that they are not suitable for precracking due to uneven fatigue crack growth through the wall [6], [15], so it is recommended to use the PRS only with the notch. *F* - CMOD curves as very important for calculating the fracture toughness are compared on PRS specimens with notch and PRS specimens with fatigue precrack on example of PRS specimen with dimensions: *D* = 114,3 mm, *B* = 12,5 mm, *W* = 25 mm. Also two states are analysed, as delivered state and stress relieved state in order to see is there any influence of the residual stresses. Since it is quite hard to obtain equal fatigue crack depth on both sides of the same ring, Figure 8 shows comparison of *F* - CMOD curves for two rings (one in delivered state and one in stress relieved state) and for both sides of the ring (COD and Aramis side) for precracked rings. So on one side of the ring, CMOD is measured with COD gauge, and on the other side with Aramis optical measuring system. Figure 9 shows comparison of *F* - CMOD curves for notched only rings also for both sides: COD and Aramis side. Figure 10 shows comparison of *F* - CMOD curves for Aramis side only because on the Aramis side ratio *a*/*W* in case of precracked rings is obtained very close to the ratio *a*/*W* in case of the only notched rings. Three point bend test is also performed on Instron 1255-8500 Plus at the Fakulteta za Strojništvo in Maribor.

Explanation of specimen designation:

PRSxx
→ „z“ - precracked specimen, „n“ - notch only specimen
→ „n“ - as delivered state, „o“ - stress relieved state
→ Pipe - Ring Specimen

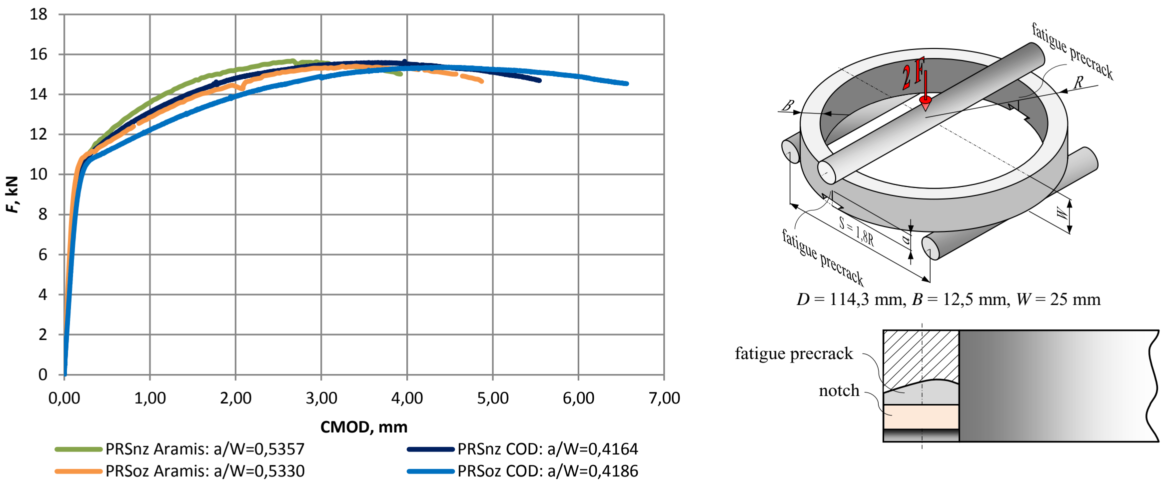


Fig.8 Comparison of COD and Aramis side in means of CMOD for precracked rings

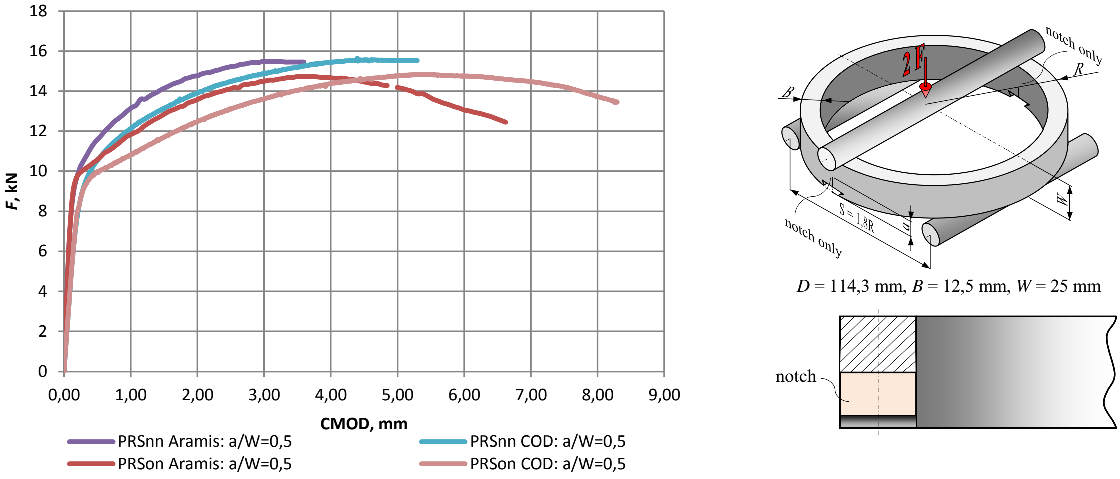


Fig.9 Comparison of COD and Aramis side in means of CMOD for notched only rings

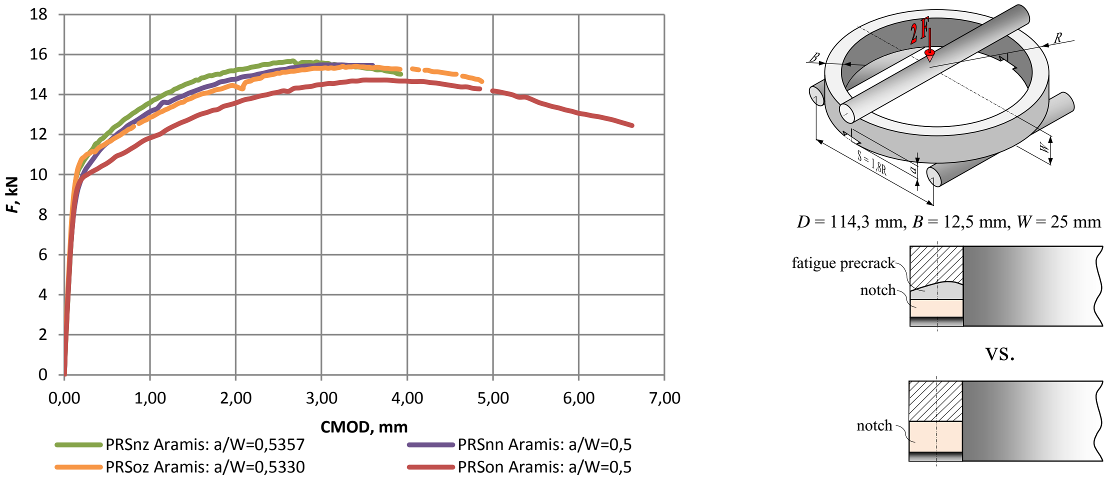


Fig.10 Comparison of Aramis side in means of CMOD for precracked and only notched rings

3. Conclusions

Results of IHDM method are averaged on way that relevant area of results is taken from 0,25 ÷ 0,85 mm of measured hole depth. That is because there are always some errors in measurement near the surface, and at the end of measurement. Results are displayed in such a way that for the equivalent specimens the mean values have been calculated, for both methods, IHDM and splitting method.

The production of seamless pipes involves hot rolling, sizing, straightening etc. in several stages. Thus, it is reasonable to expect some deviations in results when considering two same specimens (for example 5.1.1 and 5.1.2), because pipe is almost always rotating along it's longitudinal axis during manufacturing process, so entire surface of pipe is not constantly in contact with rollers. According to that, residual stresses can vary measuring on different locations around the specimen geometry.

Obviously, there are some deviations between IHDM and splitting method which are expected, because in general splitting ring method is an fast and easy control method that gives a global overview of the state of residual hoop stress in pipe.

It is important to note that by determination of residual stresses using IHDM results can vary significantly depending on the location of the measurement around the pipe specimen, but also depending on dimensions of pipe specimens which can be very different from pipe to pipe. Also, ovality and eccentricity of pipe can affect to the results. Further, it is important to note that presented results are results for the Pipe - Ring specimens where the width of specimen is in relation to the wall thickness ($W = 2 \cdot B$). Residual stresses in pipes can be with significantly larger values, and when the specimen is cut out from pipe, the length must be at least $3 \cdot D$ [16] in order to obtain residual stresses of pipe as such.

IHDM is incomparably more expensive method for measuring residual stresses in relation to the splitting method. Splitting method is the easiest, robust and fastest method for estimation of hoop residual stress in pipes giving acceptable results.

Regarding the F - CMOD data, it can be concluded that F - CMOD curves for the stress relieved specimens in general has a bit smaller amounts of force F in every increment of data (Figures 8 to 10). Further, some difference in notched only specimens (Figure 9) for the same ring for Aramis and COD side are present because it is not possible to position the specimen ideally on the machine, also because of the imperfections in geometry of the specimens (ovality, eccentricity etc.) and so on… Figure 10 shows very similar behavior of precracked rings and only notched rings. F - CMOD data for Aramis side is used for comparison because it is much closer to the $a/W = 0,5$ which is the case of notched only rings.

Due to the fact that the fatigue precracking of rings is very difficult to obtain in order to satisfy standard, and due to the fact of very similar behavior in means of F - CMOD data in case of precracked rings and only notched rings recommendation is to use only notched ring for fracture testing even when there are some residual stresses presented in the PRS specimens.

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