ESTIMATION OF RESIDUAL STRESS IN THE HOT-ROLLED PIPES

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Abstract:

The aim of this work is to estimate the residual stresses in the pipes manufactured by the hot rolling technique. Pipes manufactured by this method are mostly used in boilers and in most cases are delivered normalized, but not stress relieved too. Therefore, there are surely residual stresses present in pipes which are result of manufacturing technique, but also of uneven cooling after 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 cause 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 are stresses which are present in material after all the external loads are removed and as such, they have significant effect on the fatigue behavior 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.

1. INTRODUCTION

Within this work, residual stresses are estimated in so called Pipe-Ring specimens (PRS) which are cut out from the pipe, *Figure 1*. This kind of specimens are 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 SENB specimen from pipe wall, PRS specimen is the simplest and the cheapest alternative solution.

In [6] Likeb was analyzed PRS specimens in relation to the standard 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.

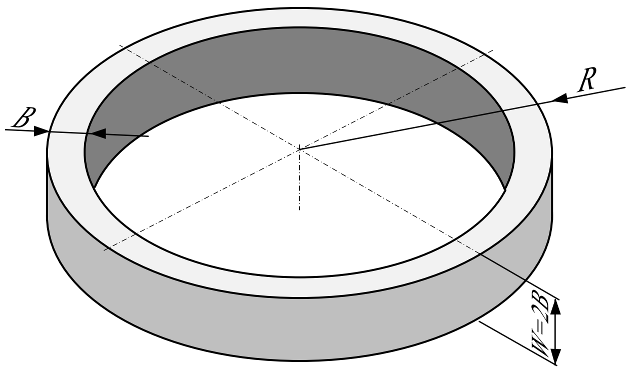


Figure 1. *Geometry of Pipe-Ring specimen (PRS)*

Since the residual stress are depend also on the dimensions of pipe, within this paper, residual stresses are measured on four different pipe dimensions varying the outside diameter and wall thickness, *Figure 2*.

Pipe label	**Outside diameter *D*, mm**	**Wall thickness *B*, mm**
5(1)	114,3	12,5
5(2)	219,1	22,2
11	168,3	8
14	193,7	7,1

Figure 2. *Dimensions of considered pipes*

All considered pipes are made from standard boiler steel 16Mo3. Furthermore, one of the aims of this paper is to apply the heat treatment of stress relieving and also to measure the residual stresses in the stress relieved specimens in order to evaluate the validity of the stress relieving heat treatment on the residual stress in this type of pipes.

2. EXPERIMENTAL PROCEDURE

Since it is quite hard to simulate all the production process numerically, the residual stresses are estimated using two methods:

- Incremental hole drilling method according to ASTM E 837-08 [7],
- Splitting method according to ASTM E 1928-99 [8].

For implementation of both methods material properties are taken from Key to steel for room temperature with values: E = 212000 MPa, ν = 0,3 [9]. Since material properties can differ from pipe to pipe in future work plan is to make tensile tests for specimens made from all four considered pipe dimensions and for two cases: as delivered condition and stress relieved condition.

According to the EN 10216-2 [10], tolerance for outside diameter 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 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.

Labels for specimens used to estimate the residual stress are shown in *Figure 3*. All specimens with “o” in label are stress relieved.

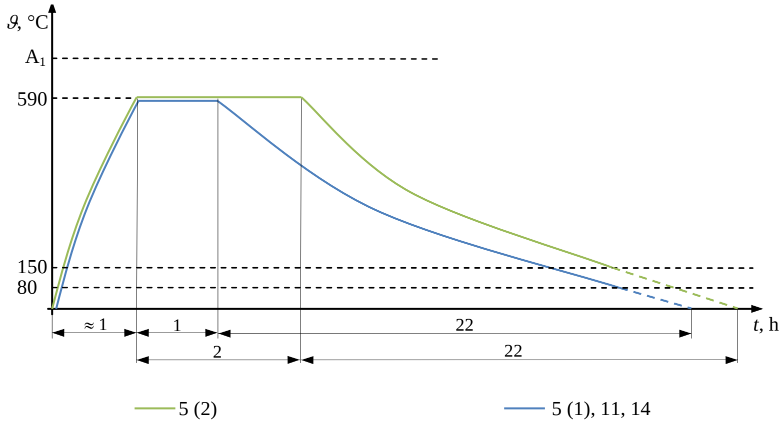
Pipe label	Specimen label	
	As delivered state	**Stress relieved state**
5 (1)	5.1.1	5.1.1.o
	5.1.2	5.1.2.o
5 (2)	5.2.1	5.2.1.o
	5.2.2	5.2.2.o
11	11.1	11.1.o
	11.2	11.2.o
14	14.1	14.1.o
	14.2	14.2.o

Figure 3. *Specimen labels*

There are 16 specimens in total, 8 for as delivered state and 8 for stress relieved state. Further, experimental setup is performed to make two measurements for each specimen type.

2.1 Stress relieving heat treatment

According to [11], holding time at the stress relieving temperature is 2 min/mm of wall thickness, but not less than 0,5 h. Further, temperature of stress relieving for steel is 550 ÷ 620 °C, so according to the [9] stress relieving temperature is taken as 590 °C exactly for steel 16Mo3. According to mentioned, holding time for specimens made from pipes 5(1), 11 and 14 is 0,5h, but holding time taken into account is doubled, so 1h. Further, calculated holding time for specimens made from pipe 5(2) is 1h, but with same analogy, holding time taken into account for this specimens is doubled, so 2h. After the holding time at stress relieving temperature has ended, furnace is shut down and all the specimens are cooled in the furnace atmosphere up to minimal 150 °C and then cooled at air up to room temperature. Stress relieving diagram for all specimens is shown on *Figure 4*, a), and furnace used for heat treatment on *Figure 4*, b).



a)

b)

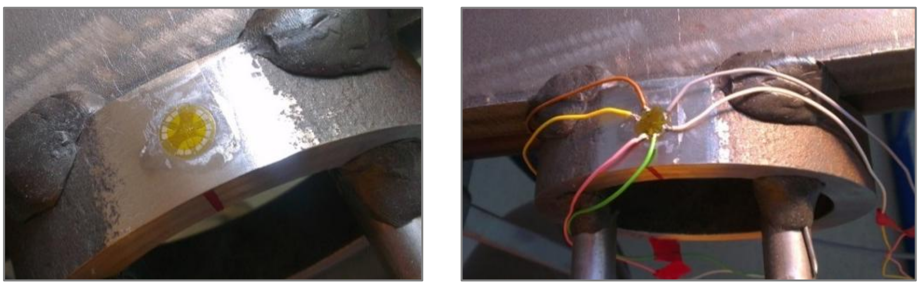
Figure 4. *Stress relieving heat treatment: a) stress relieving diagram, b) furnace Nabertherm B180*

2.2 Incremental hole drilling method

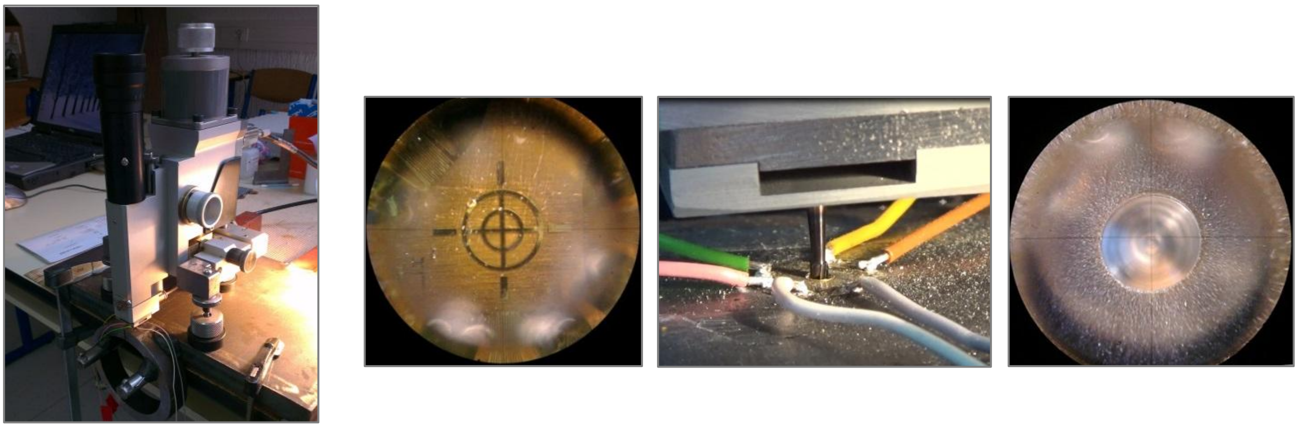
Incremental hole drilling method (IHDM) is categorized as semi-destructive method since it implies drilling the small diameter hole (d = 1,8 mm) into the material and measuring the deformation around the hole using the special developed strain gauges called strain gauge rosette. This method is one of 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 [7].

Procedure of measuring residual stresses by IHDM in general is: preparation and positioning of strain gauge rosette, preparing and positioning of measuring device. Some of steps in measuring are presented in *Figure 5* and slightly clarified in the figure caption.

a)



b)



c) d) e) f)

Figure 5. *Measuring residual stresses using IHDM: a) positioning the specimen, b) positioning and preparing the strain gauge rosette, c) positioning measuring device above the strain gauge rosette, d) centering the measuring device within the strain gauge rosette, e) performing the measure, f) measuring the hole dimensions after the process of measurement*

Example of results obtained by the IHDM on specimens made from pipe 5(1) are presented on *Figure 6*.

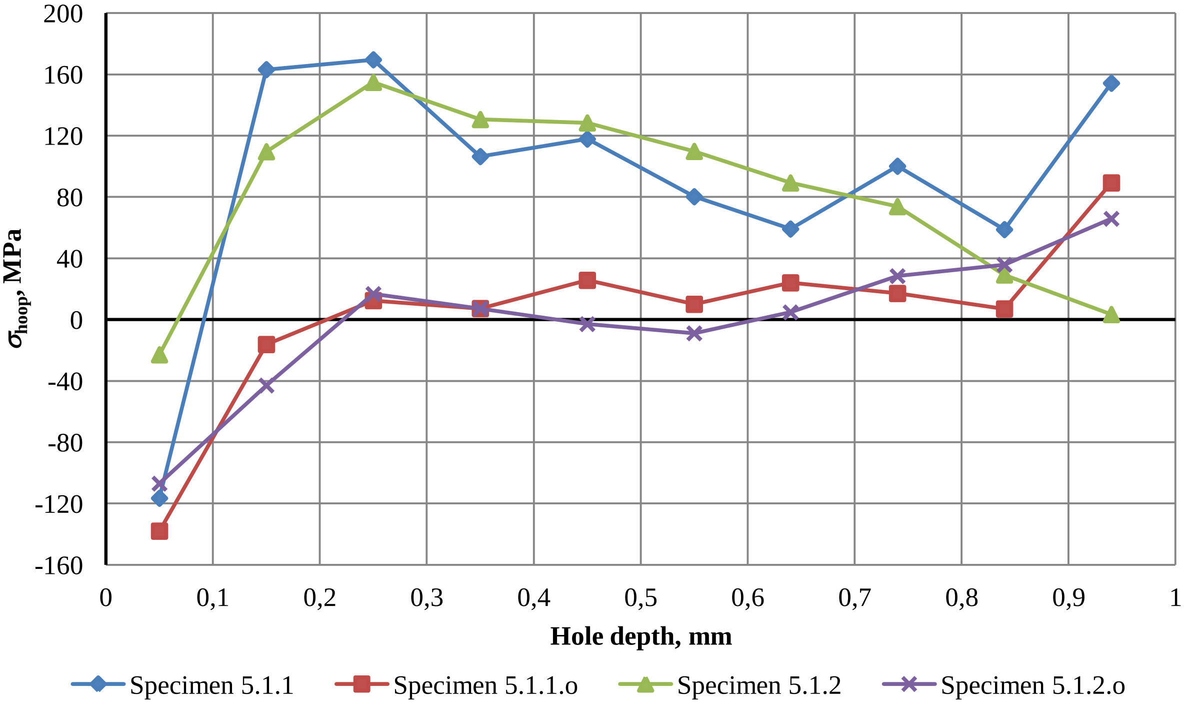


Figure 6. *Example of hoop stress results obtained by IHDM on specimens made from pipe 5(1)*

2.3 Splitting method

Quantitative estimation of residual stresses in pipes can be determined by cutting the pipe longitudinally and analyzing the change of outer diameter. Hatfield and Thirkell presented the idea firstly, and then Sachs and Espey [12] 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 7*.

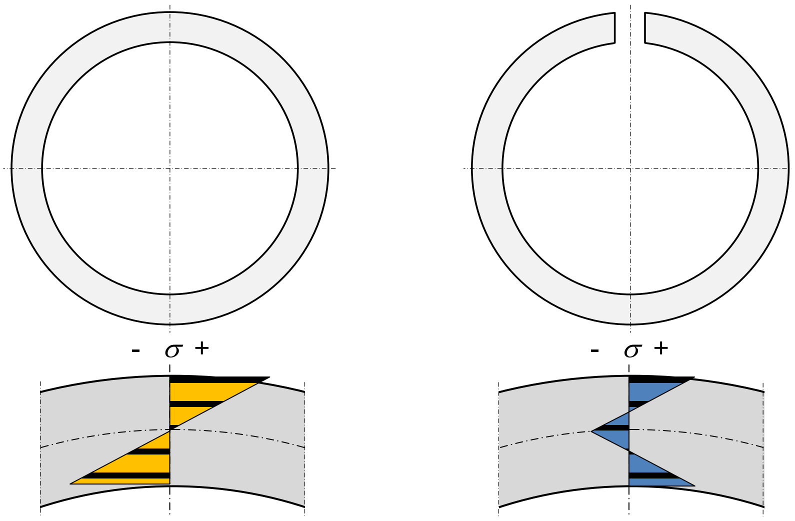


Figure 7. *Schematic of the hoop residual stress distribution in rings manufactured from pipe before and after slitting* [13]

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

$$\sigma = \pm \frac{E \cdot t}{1-\nu^2} \cdot \frac{D_f - D_0}{D_f \cdot D_0}$$

- where
  - σ - hoop stress, MPa
  - E - Young's modulus of elasticity, MPa
  - t - 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 specimens 5.1.1 and 5.1.1.o is shown on *Figure 8* and results for all specimens are presented in Heading 3. It is obvious much smaller opening of slit in case of stress relieved specimen and thus much smaller residual hoop stress.

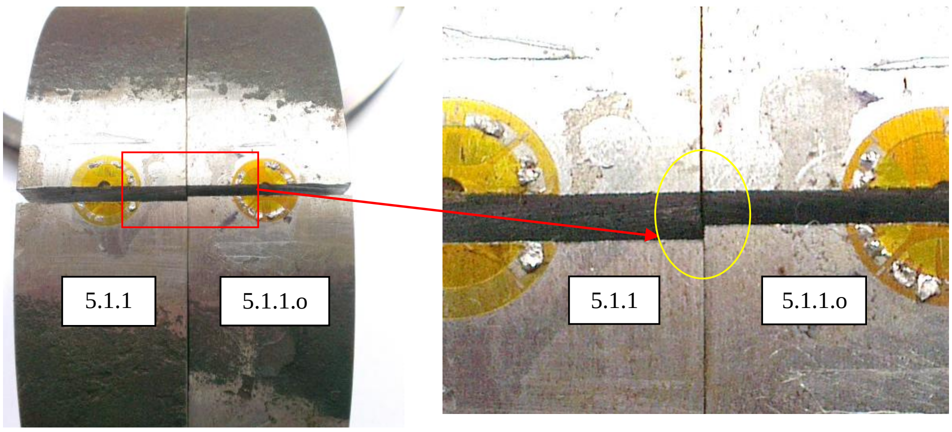


Figure 8. *Example of splitting ring method on specimens 5.1.1 and 5.1.1.o*

3. RESULTS AND CONSLUSION

Results for all specimens obtained by IHDM and splitting method are presented in *Figure 9*. Results of IHDM method are averaged on way that relevant area of results is taken from 0,25 ÷ 0,85 of hole depth. That is because there are always some errors in measurement near the surface, and at the end of measurement.

Specimen label	IHDM	Splitting method
5.1.1	98,85	81,31
5.1.1.o	14,78	11,78
5.1.2	102,25	59,64
5.1.2.o	11,58	11,8
5.2.1	34,2	75,98
5.2.1.o	2,9	10,82
5.2.2	79,73	16,37
5.2.2.o	4,67	5,42
11.1	68,82	82,21
11.1.o	33,91	24,8
11.2	13,33	111,83
11.2.o	15,22	32,69
14.1	88,72	75,67
14.1.o	4,97	-13,56
14.2	32,33	70,91
14.2.o	7,35	-2,58

Figure 9. *Comparison of results obtained by 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 5.2.1 and 5.2.2), 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, so final results are determined using the average values obtained by two specimens for each type of pipe and condition. Final results are shown on *Figure 10*.

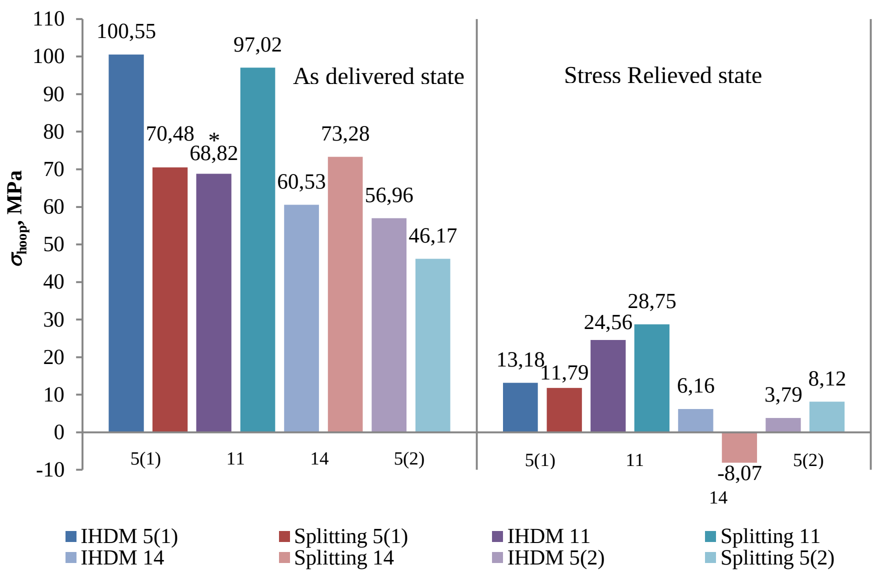


Figure 10. *Final results of residual hoop stress*

Obviously, there are some deviations between IHDM and splitting method which are expected, because in general Splitting ring method is an easy control method that gives a global overview of the state of residual hoop stress in pipe. Furthermore, there is also some compressive residual stress obtained by splitting method after stress relieving heat treatment in the specimens manufactured from pipe with label 14.

*In case of specimens manufactured from pipe with label 11, only one specimen measured with IHDM is taken into consideration because some error and uncertainty in measurement was present in another one.

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.

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