

The evaluation of the elasto-plastic behavior in case of the honed steel pipes subjected to variable internal pressure

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Abstract. The paper analyses the elasto-plastic behavior of ten samples of E355 steel pipe of the same inner diameter, but with wall thickness ranging between 1.100 and 2.500 mm and length about 100 mm. The samples were subjected to variable internal pressure which was increased from 0 to 600-800 bar (up to the breaking of the pipe), being used the hydraulic oil, type HM46. The outer diameter of the tested pipes was measured successive for each increase of pressure with 100 bars, thus being determined the flow curve of the pipe material characterized by the elasto-plastic behavior and a tenacious failure. It was found that thin pipes, with the ratio between the inner and outer diameter less than 1.1, shows a different flow curve compare to pipes with thick walls, having the ratio between the inner and outer diameter greater than 1.1, the deformations being about two times higher. The rheological models of each type of pipes were identified.

1. Introduction

Steel pipes which do not imply welding and have small diameters are frequently used in various industrial applications, such as: mechanical, automotive, aeronautic, petrol, natural gases, chemical and petrochemical, energetic and hydraulic industry. Depending on the domain of usage, these pipes may be subjected to mending or anticipated processing, like chroming, galvanization, rectification, honing etc [1, 2]. For example, in order to produce hydraulic cylinders, steel pipes are honed to obtain a resistant surface and roughness between 0.2 to 0.012 μm . The characteristics of the steel used to obtain honed pipes are known; allowing precise strength calculus, which leads to correct dimensioning and to the reduction of safety coefficients. Steel is an isotropic material which can be stressed in all directions, to both traction and compression, considering the admissible limits. The prediction of the behavior in time of pipes in the visco – elasto - plastic domain represents an important aspect, especially in the case of pipes existing at the limit between pipes with thin walls and those with thick walls. Considering the strength calculus of the pipes' tubing two cases appear: the case of thin walled pipes – characterized by the ratio exterior diameter D_e to interior diameter D_i less than 1.1: ($\beta = \frac{D_e}{D_i} \leq 1.1$), and the case of the thick walled pipes – characterized by the ratio $\beta = \frac{D_e}{D_i} > 1.1$. The variation and the value of the interior pressure, the thickness of the pipe's wall, as well as the environmental factors influence the values of the axial and radial deformations. Thus, the failure of the material propagates from the interior towards the exterior of the pipe, and the crack appears on the generator's direction [3-6]. The numerous studies on the elastic-plastic behavior of pipes subjected to internal pressure led to the development of theories to predict the burst failure at plastic collapse for pipes [7 -

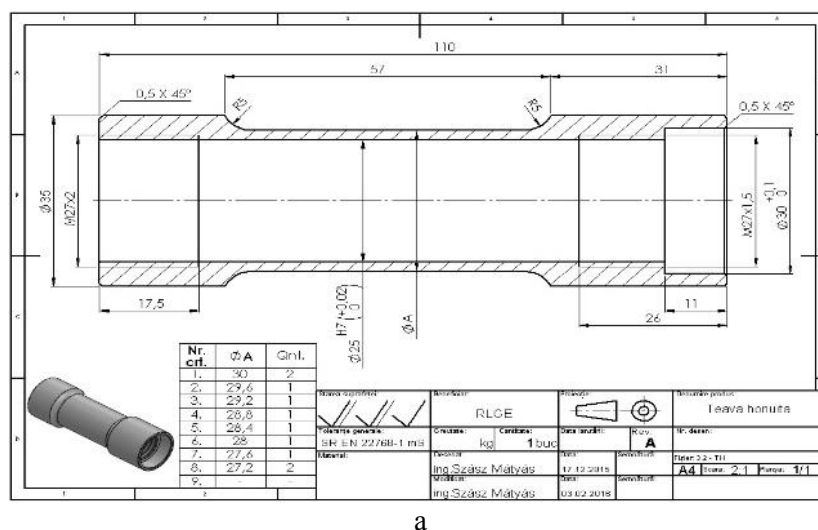


10]. Zhu and Leis have introduced into study the plastic flow effect concerning of elasto-plastic response of pipes which is based on the maximum shear stresses [7]. Reference [10] revealed the mechanism of appearance and crack propagation in gas pipelines, noting that plastic deformations extend before cracks become unstable. Knowing elastic-plastic phenomena and when material of pipe subjected to internal pressure moving from one state to another are valuable information for predicting damage and ensure regular inspections [11 - 14]. In the current study, the testing of the honed pipes has been completed by means of a hydraulic system, where the samples have been subjected to variable internal pressure. The specimens, obtained from OL 335, have different wall thickness varying between 1.105 mm to 2.505 mm. The pipes' walls deformation was periodically measured throughout the tests, and their rheological behavior and the material's microstructure in the failure area have been analyzed.

2. The experimental method

2.1. The analysis of the specimens

Parts of honed pipes with length of 110 mm and the interior/exterior diameter of $\varnothing 25/35$ made from E355 steel (St52; 1.0580; Fe510), and having a chemical composition expressed in (%): C – 0.140/ SI – 0.340/ MN – 1.330/ P – 0.007/ S – 0.019/ AL – 0.026, characterized by the admissible yield stress (σ_c): 548 N/mm² and the maximum stress (σ_r): 722 N/mm² (figure 1, a) were submitted to pressure tests.



a



b

Figure 1. The geometry of the tested samples: a) pipe section; b) types of samples.

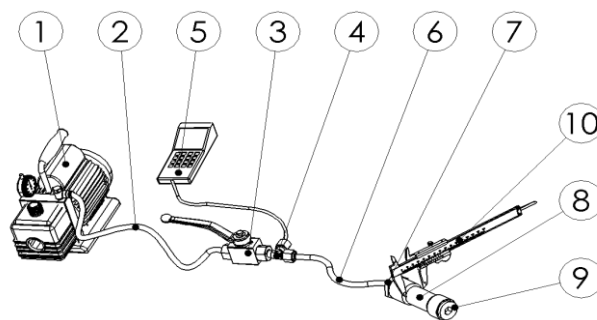
The shape and design of the specimens were executed on a computer numerical control machine according to EN 10305-1: 2010. The specimens were executed with high precision being measured and labeled (figure 1, b). The resulting dimensions are presented in table 1.

Table 1. Dimensions of the specimens before testing.

Samples Code	Interior diameter D_i [mm]	Exterior diameter D_e [mm]	Thickness of the wall h [mm]	Length L [mm]	$\beta = D_e/D_i$
1.1.1	25	30.01	2.505	109.87	1.2004
1.1.2	25	29.99	2.495	109.50	1.1996
1.2	25	29.60	2.300	109.85	1.1840
1.3	25	29.20	2.100	109.53	1.1680
1.4	25	28.80	1.900	109.82	1.1520
1.5	25	28.40	1.700	109.57	1.1360
1.6	25	28.00	1.500	109.60	1.1200
1.7	25	27.60	1.300	109.70	1.1040
1.8.1	25	27.22	1.110	109.74	1.0888
1.8.2	25	27.21	1.105	109.74	1.0884

2.2. Testing method

The experimental assembly used for the testing of the specimens includes the following components (figure 2): (1) electric pump with the electric current consumption of 4.5 A and which works at a 50 Hz frequency, at a maximum pressure of 800 bars; (2) hydraulic hose obtained in conformity with the European standards (730 EN 856), with 4 metallic insertions (4SP), with a nominal diameter of 6 mm (DN6) resisting up to 450 bars, $l=2000$ mm; (3) faucet type KHB – D/4'', with a nominal diameter of 6 mm (DN6) and a nominal pressure of 500 bars (PN500); (4) T-shaped connector of 1/4'' on which is attached a measuring hex-nipple; (5) supplementary manometer of 1000 bars; (6) hydraulic hose obtained in conformity with the European standards (730 EN 856), with 4 metallic insertions (4SP), with a nominal diameter of 6 mm (DN6) resisting up to 450 bars, $l=500$ mm; (7) joint bushing including locking bushing M27x1.5, and, oppositely, joint hex-nipple M118x1.5 designed to support a maximum pressure of 800 bars, while the sealing is made with a rubber ring (NBR) with the dimensions 2.5x2.62 mm; (8) testing specimen; (9) metallic cork with gasket; (10) electronic caliper to measure the exterior diameter during traction. While testing, the specimens were introduced inside a protection pipe to avoid accidents.

**Figure 2.** Scheme of the experimental assembly.

Each specimen has been subjected to the same internal pressure with hydraulic oil regime. The test has been developed with pressure increasing in stages from 0 to 800 bars, where the exterior diameter has been measured from 100 to 100 bars, and close to the admissible tensile stress the pitch was 50 bars. Testing under pressure of the honed pipe parts lasted almost 15 minutes for each specimen. The structure of the failure and the propagation direction of the crack were analysed by means of digital microscope where even the composition and the microstructure of the steel were visible.

3. Results and discussion

During data processing, the rheological models for the analyzed specimens have been determined based upon the variation curves pressure to deformation. Each specimen was exposed to the same interior pressure regime of 0-800 bars with the interior pressure variation of 100 bars (in the interval 0-500 bars), and 50 bars, respectively (in the interval 500-800 bars). Figure 3 shows the variation curves of the deformations with respect to the interior pressure.

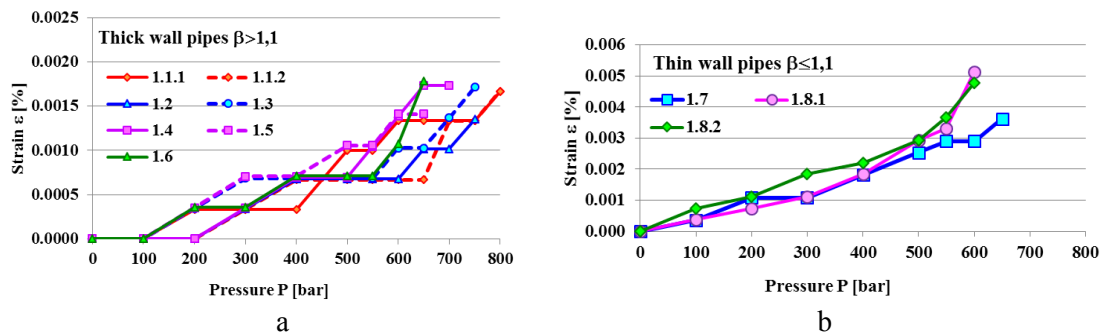


Figure 3. Variation of strains with respect to pressure: a) thick walled pipes; b) thin walled pipes.

Thus, the rheological model of the thick walled pipes includes a Saint Venant type of element (plastic) parallel connected to a Newton type of element (figure 4, a). The deformation of the thick walled pipes at the staged, variable interior pressure presents in the shape of a plastic response followed by a viscous response [15-17]. In case of the thin walled pipes, the response is primarily elastic, after which, when the interior pressure exceeds the elasticity limit of the pipe's material, the deformations take place in plastic domain (figure 4, b). The specimen found at the border between the two categories of thin and thick walled pipes ($\beta = 1.1$) presents a rigid-elastic-plastic behavior, its rheological model including an elastic element type Hooke, series connected to a parallel group type Maxwell-Saint Venant (figure 4, c).

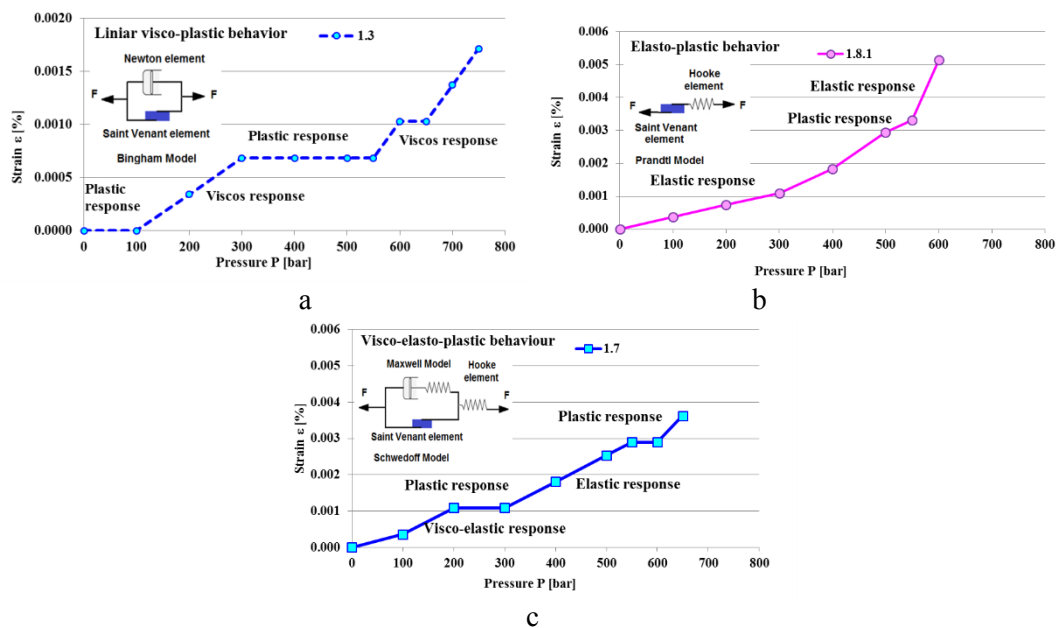


Figure 4. Rheological response: a) linear visco-elastic (Bingham model); b) linear elasto-plastic (Prandtl model); c) Visco-elasto-plastic behaviour (Schwedoff model).

Considering the way in which the pipes subjected to interior pressure failed, it can be observed that the failure appeared on the longitudinal axis, which is specific to tenacious material (figure 5, a). The maximum pressure when the failure occurred varies for the thick walled pipes between 650 and 800 bars, and for the thin walled pipes, between 550-600 bars. The micrographic analysis by optic microscope highlights the propagation areas of the crack, the elastic behavior areas and those with plastic behavior (figure 5, b) [18, 19].

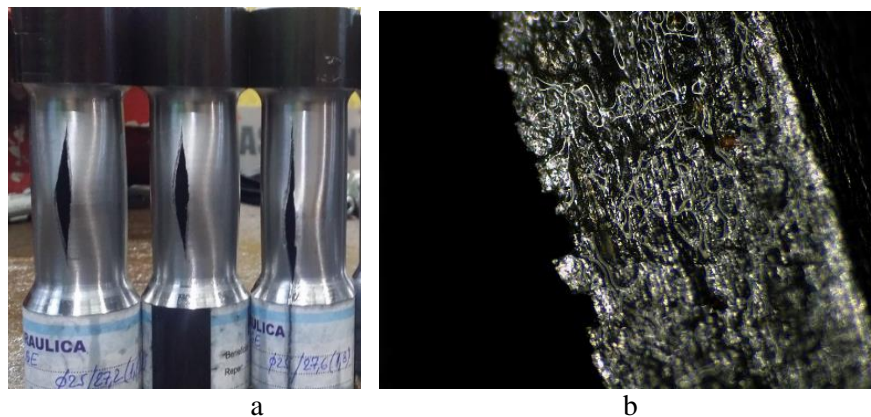


Figure 5. a) Failure area for the tested specimens; b) Optical micrograph scanning of 200x of the failed area in case of specimen 1.8.1. (thin wall).

4. Conclusions

Based on the experimental testing the rheological models of the visco - elastic - plastic behaviour of the thick and thin walled pipes have been determined. The strength, lifetime and mechanic response of the steel pipe type structure are influenced by composition, purity of the material, quality of processing, geometrical characteristics and applied internal pressure. It was found that the wall thickness of the pipe plays an important role in elastic-plastic behavior. If thick-walled pipes, the prediction method of pipe failure is based on interpolation of the visco - elastic response and the plastic limit load. For thin-walled pipes and the borderline between thick and thin wall, the determining of the plastic behavior is more difficult because the plastic response occurs in non-linear domain, depending on the elastic limit state.

Determining the strain rate during pipe loading under internal pressure assume the approximating rheological models based on their response. The behavior differs depending on the type of loading: in case of static loading, strains and strain rate depend on the ductility of the pipe material and pick of pressure; if the dynamic load, the strains and strain rate depend on the pressure waveform. Based on experimental determinations presented in the paper, can be approximated the critical limit of strains.

In order to safely use and guarantee a long lifetime of the honed steel pipes, the external factors (internal pressure, external pressure, temperature, humidity, corrosive factors) which may change the behaviour of the steel pipes, must be taken into consideration.

Acknowledgments

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