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QUASI-STATIC LOADING OF PIPING WELDED JOINTS

Andrzej Klimpel [1], Krzysztof Herbuś [2], Piotr Ociepka [2], Anna Timofiejczuk [3], Massimiliano Pedot [3]

[1] The Silesian University of Technology, The Faculty of Mechanical Engineering, The Department of Welding
Konarskiego 18A, 44-100 Gliwice, Poland
[2] The Silesian University of Technology, The Faculty of Mechanical Engineering, The Department of Engineering Processes Automation and Integrated Manufacturing Systems
Konarskiego 18A, 44-100 Gliwice, Poland
[3] The Silesian University of Technology, The Faculty of Mechanical Engineering, The Department of Fundamentals of Machinery Design
Konarskiego 18A, 44-100 Gliwice, Poland

Corresponding author: Krzysztof Herbuś, krzysztof.herbus@polsl.pl

Abstract: One of the main issues in relation to the pipe system design process is the analysis of the quality and strength of joints occurring in them. The analysis is necessary because of the possibility of a damage of these systems that could cause dangerous incidents in relation to the safety of people and the environment. The most common cause of this type of the danger is the sudden appear unexpected catastrophic or quasi-static loads. The paper presents a series of numerical and experimental tests of the impact of quasi-static loads on the character of deformations and the strength of the welded joint of pipes made of API 5LX80 material. In the first stage of the work, the strength analysis of the pipe without a weld joint and with a weld joint was performed using the finite element method (FEM). The purpose of this analysis was to identify the load causing the strain of the specimen to the strength limit of the material used. Based on the identified load, experimental tests were performed on a pipe specimen with a weld joint. Obtained results of numerical and experimental tests allowed determining the maximum load causing the strain of the material at which the weld joint is not damaged.
Key words: piping, welded joint, API 5LX80 material, nonlinear strength analyses, flattening tests.

1. INTRODUCTION

The piping systems of refinery plants are generally considered to include the complete inter-connection of pipes, including in-line components such as pipe fittings and flanges and most critical – welded joints, (Figure 1) [2,4,5,8,9,11-14]. Pumps, heat exchanges, valves and tanks are also considered part of piping system. Piping systems are the arteries of refinery plants industrial processes and the contribution of piping systems are essential form point of view of efficiency and safe service of the plants. The initial design of a piping system is established by the functional requirements of piping a fluid from one point to another. The detailed design is decided by criteria such as type of fluid being transported, allowable pressure drop or energy loss, desired velocity, space limitations, process requirements like free drain or requirement of straight run, stress analysis, temperature of fluid, etc. [4, 5, 13]. The structural integrity and fitness for service of refinery piping installations and welded joints in specific require understanding of specific threats, mainly unexpected catastrophic impact loads due to e.g. collapse of nearby structures like walkways, vessels, towers, etc. Piping systems are designed, fabricated, and operated to ensure a very high level of structural integrity because the consequences of structural failures can be very severe when specifically fire damages take place [2]. The results of catastrophic failure are increased risks to personnel, high economic losses and concern regarding the safe plant operation. The weakest and the most sensitive areas of piping systems are any kind of joints, but specifically flange bolted joints and welded joints, despite of the modern quality assurance systems commonly used in the case of piping installations of refinery plants. In case of welded joints, the main objective is to gain knowledge on an influence of catastrophic impact and quasi-static loads of welded joints on their properties, which can be useful in safe designing of piping systems to avoid the catastrophic failure of the refinery plants. Pipe Diameter Factor (PDF), one of basic failure factors of piping systems, considers that the bigger the pipe diameter, the greater the potential severity of failure. For instance, the consequence factor for a pipe of 12 inches (304 mm) in diameter is higher than a factor for a pipe of 8 inches (203.2 mm). As the most modern and typical solution of piping installations API 5LX80 high strength steel pipes 323.9 mm (12.75 inches) diameter and 10 mm wall thickness were selected and four welding processes were used to produce specimens for quasi-static tests: Manual Metal Arc (MMA), Gas Metal Arc (GMA), Speed Short Arc (SSA), and laser + GMA. To simulate catastrophic quasi-static loading of MMA, GMA, SSA and LASER + GMA butt welded joints of piping installations the following study were done:

- FEM modelling to calculate the value of the force needed to flatten [1,3,7] the butt welded joints of API 5LX80 pipes as per EN ISO 8492:2004 (Figure 2) [6],
- Quasi-static loading experiments of butt welded joints specimens.

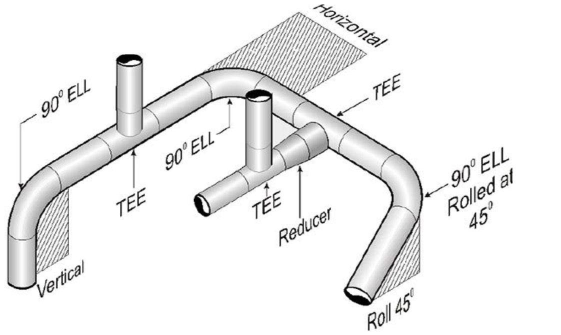


Fig. 1. A view of typical elements of the refinery piping installation where pipes butt joints are welded in horizontal – PC (2G) and vertical position – PH (5G) [2,8,9]

In the Figure 2 was presented guidelines for the process of flattening pipes during strength tests. In the work, the value of the force necessary to obtain a plastic deformation of the pipe to an intermediate form between the undeformed pipe and the completely flattened pipe, was determined using of numerical analyzes.

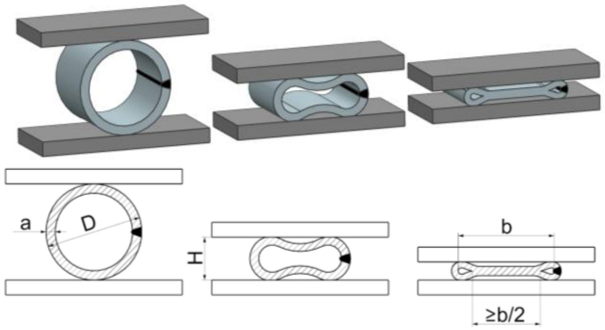


Fig. 2. Metallic materials – Tube – Flattening test as per EN ISO 8492:2004 , H – flattening parameter = 66% x A for parent material or 70% x A for welded joint of the tube

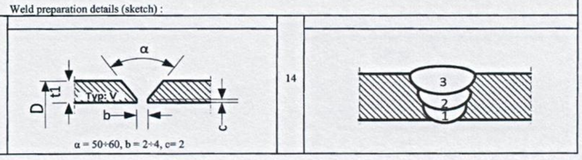
2. PREPARATION OF SPECIMENS OF BUTT WELDED JOINTS OF PIPES

To prepare the butt welded joints specimens of API 5LX80 pipes 323.9 mm diameter and wall thickness 10 mm [10] for catastrophic impact and quasi-static loading experiments, the Welding Procedure Specifications - WPS were worked out in Mostostal S.A. Zabrze, Poland. The WPS's of three basic welding processes, commonly used in production of piping systems of refinery plants: MMA, GMA and SSAW, and one, the most modern solution of butt pipe joints welding process – root pas laser welded and filling and cap passes – GMA welded, was presented in the Figure 3 and Figure 4.

a) **Welding Procedure Specification** — **WPS-MMA-01** Rev. **00**

1	WPQR 1 nr:	N/A	8	Examiner / test body:	N/A
2	WPQR 2 nr:	N/A	9	Method of preparation and cleaning	Mechanical
3	Location:	Gliwice / Poland	10	Material thickness „t" [mm]:	10,01
4	Welding process	111 (MMA)	11	Outside diameter „D" [mm]:	323,9
5	Joint type:	BW	12	Welding position:	PC (2G) / PH (3G)
6	Parent material specification	API 5L X80			
7	Weld preparation details (sketch) :				

13, 14



15 WELDING DETAILS

Run		Process	Size of filler metal [mm]	Curent [A]	Voltage [V]	Type of curent / Polarity	Travel speed [cm/min]	Heat imput [kJ/cm]
PC / 2G								
1	root run	111	2,5	65 ÷ 75	21,0 ÷ 23,0	DC +	5,0 ÷ 7,0	9,4 ÷ 16,6
2	layers of filling runs	111	3,2	115 ÷ 125	23,0 ÷ 26,0	DC +	16,0 ÷ 24,0	5,5 ÷ 9,8
4	layer of capping run	111	3,2	115 ÷ 125	23,0 ÷ 26,0	DC +	16,0 ÷ 24,0	5,5 ÷ 9,8
PH / 3G								
1	root run	111	2,5	65 ÷ 75	21,0 ÷ 23,0	DC +	3,0 ÷ 5,0	13,1 ÷ 27,6
2	layers of filling runs	111	3,2	110 ÷ 120	23,0 ÷ 26,0	DC +	12,0 ÷ 16,0	7,6 ÷ 12,5
4	layer of capping run	111	3,2	110 ÷ 120	23,0 ÷ 26,0	DC +	12,0 ÷ 16,0	7,6 ÷ 12,5

16	Filler metal:		22	Preheat temperature:	min. 100°C
	Classification:	AWS A5.5 E12018-G-H4R EN ISO 18275-A: E 69 5 Mn2NiCrMo B 3 2 H5	23	Interpass temperature:	max. 250°C
17	Trade name:	Conarc 85	24	Post- weld heat treatment:	N/A
18	Any special backing or drying	vacuum pack	25	Time, method:	N/A
19	Gas / flux:		26	Heating rates:	N/A
	- shielding:	N/A	27	Cooling rates:	N/A
	- backing:	N/A	28	Other information:	N/A
20	Gaz flow rate:		29	Welding details:	N/A
	- shielding:	N/A			
	- backing:	N/A			
21	Tungsten electrode type/size:	N/A			

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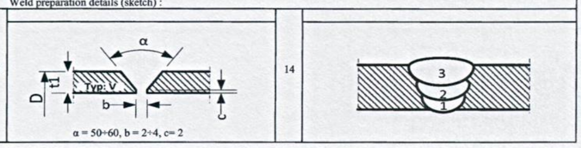
b) **Welding Procedure Specification** — **WPS-GMA-01** Rev. **00**

1	WPQR 1 nr:	N/A	8	Examiner / test body:	N/A
2	WPQR 2 nr:	N/A	9	Method of preparation and cleaning	Mechanical
3	Location:	Gliwice / Poland	10	Material thickness „t" [mm]:	10,01
4	Welding process	135 (GMA)	11	Outside diameter „D" [mm]:	323,9
5	Joint type:	BW	12	Welding position:	PC (2G) / PH (3G)
6	Parent material specification	API 5L X80			
7	Weld preparation details (sketch) :				

13, 14



15 WELDING DETAILS

Run		Process	Size of filler metal [mm]	Curent [A]	Voltage [V]	Type of curent / Polarity	Travel speed [cm/min]	Heat imput [kJ/cm]
PC / 2G								
1	root run	135	1,2	100 ÷ 110	16,0 ÷ 19,0	DC +	10,0 ÷ 13,0	5,9 ÷ 10,0
2	layers of filling runs	135	1,2	190 ÷ 220	21,5 ÷ 23,5	DC +	28,0 ÷ 34,0	5,8 ÷ 8,9
4	layer of capping run	135	1,2	190 ÷ 220	21,5 ÷ 23,5	DC +	28,0 ÷ 34,0	5,8 ÷ 8,9
PH / 3G								
1	root run	135	1,2	90 ÷ 105	16,0 ÷ 18,0	DC +	9,0 ÷ 12,0	5,8 ÷ 10,1
2	layers of filling runs	135	1,2	160 ÷ 180	18,0 ÷ 20,0	DC +	22,0 ÷ 28,0	5,0 ÷ 12,3
4	layer of capping run	135	1,2	160 ÷ 180	18,0 ÷ 20,0	DC +	12,0 ÷ 16,0	8,6 ÷ 14,4

16	Filler metal:		22	Preheat temperature:	min. 100°C
	Classification:	AWS A5.28 ER110S-G EN ISO 16834-A G 69 4 M Mn3Ni1CrM	23	Interpass temperature:	max. 250°C
17	Trade name:	LNM MoNiVa	24	Post- weld heat treatment:	N/A
18	Any special backing or drying	N/A	25	Time, method:	N/A
19	Gas / flux:		26	Heating rates:	N/A
	- shielding:	EN ISO 14175-M21-ArC-20	27	Cooling rates:	N/A
	- backing:	N/A	28	Other information:	N/A
20	Gaz flow rate:		29	Welding details:	N/A
	- shielding:	12÷16 l/min			
	- backing:	N/A			
21	Tungsten electrode type/size:	N/A			

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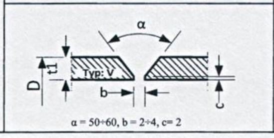
c)

	Welding Procedure Specification	WPS-SSAW-01 Rev. 00

1	WPQR 1 nr:	N/A	8	Examiner / test body:	N/A
2	WPQR 2 nr:	N/A	9	Method of preparation and cleaning	Mechanical
3	Location:	Gliwice / Poland	10	Material thickness „t" [mm]:	10,01
4	Welding process	114 (SSAW)	11	Outside diameter „D" [mm]:	323,9
5	Joint type:	BW	12	Welding position:	PC (2G) / PH (3G)
6	Parent material specification	API 5L X80			
7	Weld preparation details (sketch) :				

13


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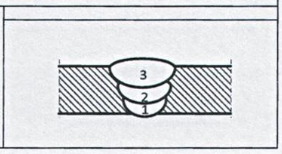

15 WELDING DETAILS

Run		Process	Size of filler metal [mm]	Curent [A]	Voltage [V]	Type of curent / Polarity	Travel speed [cm/min]	Heat imput [kJ/cm]
PC / 2G								
1	root run	114	2,0	110 ÷ 120	16,0 ÷ 19,0	DC -	8,0 ÷ 12,0	7,0 ÷ 13,7
2	layers of filling runs	114	2,0	180 ÷ 200	21,0 ÷ 24,0	DC -	25,0 ÷ 35,0	5,2 ÷ 9,2
4	layer of capping run	114	2,0	180 ÷ 200	21,0 ÷ 24,0	DC -	25,0 ÷ 35,0	5,2 ÷ 9,2
PH / 3G								
1	root run	114	2,0	110 ÷ 120	16,0 ÷ 19,0	DC -	7,0 ÷ 9,0	9,4 ÷ 15,6
2	layers of filling runs	114	2,0	150 ÷ 170	20,0 ÷ 23,0	DC -	15,0 ÷ 20,0	7,2 ÷ 12,5
4	layer of capping run	114	2,0	150 ÷ 170	20,0 ÷ 23,0	DC -	15,0 ÷ 20,0	7,2 ÷ 12,5

16	Filler metal:		22	Preheat temperature:	min. 100°C
	Classification:	AWS A5.29: E81T8-G	23	Interpass temperature:	max. 250°C
17	Trade name:	PIPELINER NR-208-XP	24	Post- weld heat treatment:	N/A
18	Any special backing or drying	N/A	25	Time, method:	N/A
19	Gas / flux:		26	Heating rates:	N/A
	- shielding:	N/A	27	Cooling rates:	N/A
	- backing:	N/A	28	Other information:	N/A
20	Gaz flow rate:		29	Welding details:	N/A
	- shielding:	N/A			
	- backing:	N/A			
21	Tungsten electrode type/size:	N/A			

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Fig. 3. The WPS's of MMA (a), GMA (b) and SSAW (c) welding processes used to produce specimens of butt welded joints of API 5LX80 pipes 323.9 diameter and wall thickness 10 mm

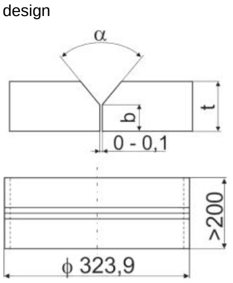
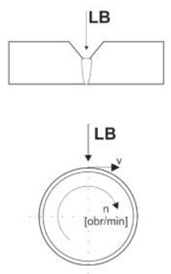
Welding Procedure Specification acc. to PN-EN ISO 15609-4:2009	**WPS 01LB/IS/B4/301/2019**
1. **Manufacturer: Łukasiewicz - Instytut Spawalnictwa ul. Bł. Czesława 16-18 44-100 Gliwice**	2. **Welding Process**: /solid state laser welding (521) **acc. to PN-EN ISO 4063:2011**
3. Equipment identification: Laser Source and Beam Implant System: TruLaser Robot 5120 station: Kuka robot KR30HA with rotational – tilting positioners KUKA DKP-400 and TruDisk 12002, Beam Quality: BPP ≤ 12mm·mrad Beam Polarisation: random, Beam Delivery System: fiber 400 μm LLK-D Beam Focusing System: TRUMPF D70, f_c = 200 mm, f_{og} = 400 mm, d_{og} = 0,8 mm Plasma Suppression Gas System: **no** Plasma Shielding Gas System: Argon - gas nozzle no 6 Filler Material Feeding System: **no**	
4. Parent Material Specification: **API 5L X80**	
5. Wall thickness: **10,0** mm, root face **6,0** mm	6. Pipe Outside Diameter:**323,9 mm**
7. Filler or other additional material: **no**	
8. Joint type: butt joint acc. to PN-EN ISO 17659:2008	
9. Joint design  t = 10 mm, b = 6 mm, α = 60°	10. Welding technique 
11. Jigs, Fixtures and Tooling: **no**	12. Mechanically Fixed: **YES** By 4 clamps welded inside on the perimeter of the tube
15. Back support: **no**	14. Backing gas: **no**

Fig. 4. The WPS of root pass laser welding of butt welded joints of API 5LX80 pipes 323.9 diameter and wall thickness 10 mm

The tables in Figures 3 and 4 show the parameters of the used pipe welding methods and the method of beveling pipe for making welded joints.

3. QUASI-STATIC LOADING OF MMA, GMA, SSA AND LASER+GMA BUTT WELDED JOINTS OF API 5LX80 PIPES

3.1 FEM nonlinear analysis of API 5LX80 pipes and the butt welded joints

As a part of the research, a non-linear strength analysis of a specimen pipe made of API 5L X80 was carried out using PLM Siemens NX software. The solver Multi-step Nonlinear (sol 401) was used to solve the presented problem. In the first step, a 3D model of the analyzed pipe specimen was created, characterized by the following dimensions: external diameter 323.9 mm, length 240 mm and thickness 10 mm. In the next step, based on the catalog data of the pipe manufacturer (Yield Strength - 618 MPa, Tensile Strength - 700 MPa, Young's module in relation to the linearly elastic part is 206 000 MPa), the non-linear properties of the pipe material (API 5LX80 - Figure 5). In the next stage of the work, the 3D model of the pipe specimen was discretized using finite elements of the CHEXA(8) type and the boundary conditions of the virtual experiment were defined (Figure 6). Were defined in a simplified way. The conducted research referred to two cases: a pipe without a weld joint and a pipe with a modeled V-type weld joint (Figure 9). In the Figure 7 and Figure 8 the results of the analyzes carried out in the form of contour lines of displacements and stresses of the analyzed objects in relation to the pipe without weld joint and in the Figure 10 and Figure 11 with reference to the pipe with weld joint were presented, while the Figure 12 presents a comparison of the stress distribution in relation to both cases. It can be seen that the stress distribution in a specimen with a modeled weld joint differs from the stress distribution in a specimen without a weld joint, which is due to other material properties of the weld joint.

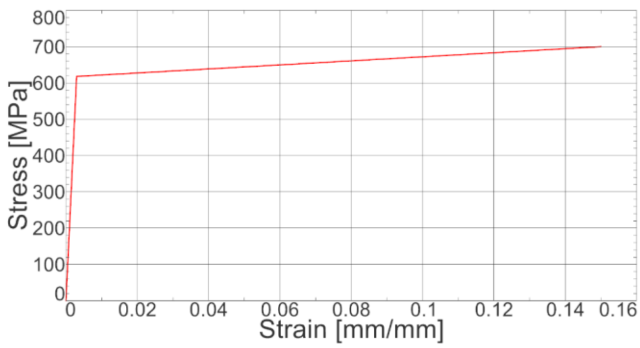


Fig. 5. The approximate Stress-Strain curve for the analyzed steel used in the FEM model

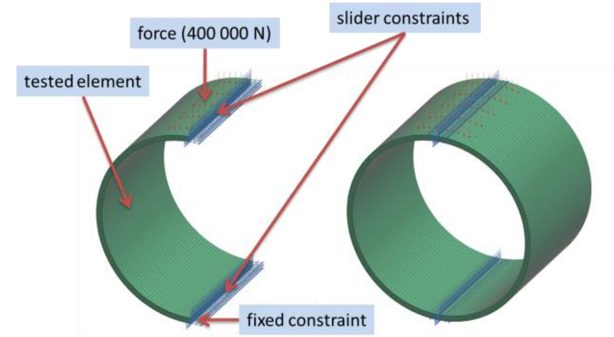


Fig. 6. The simplified model and boundary conditions of the strength analysis (the model without the weld joint)

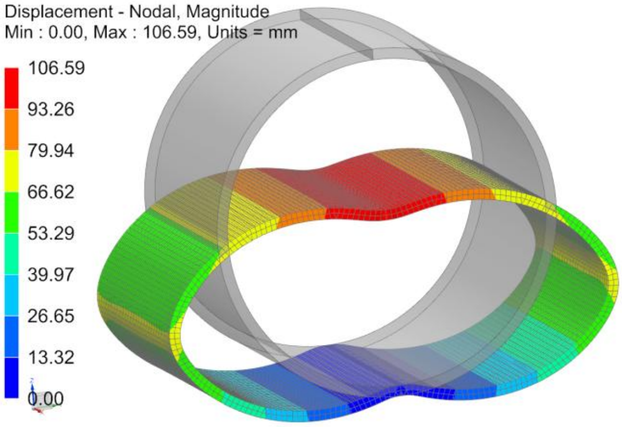


Fig. 7. The distribution of the displacement and the deformation in relation to the analysed model (the model without the weld joint)

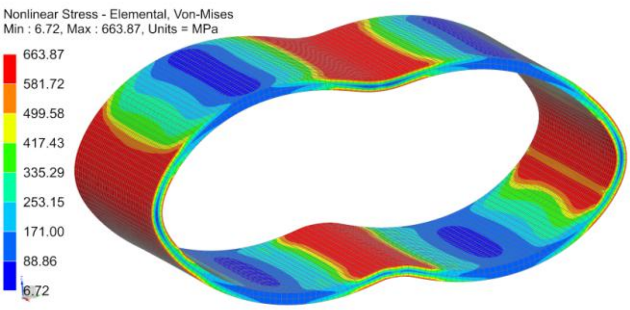


Fig. 8. The distribution of stress (Von-Mises) in the analysed model (the model without the weld joint)

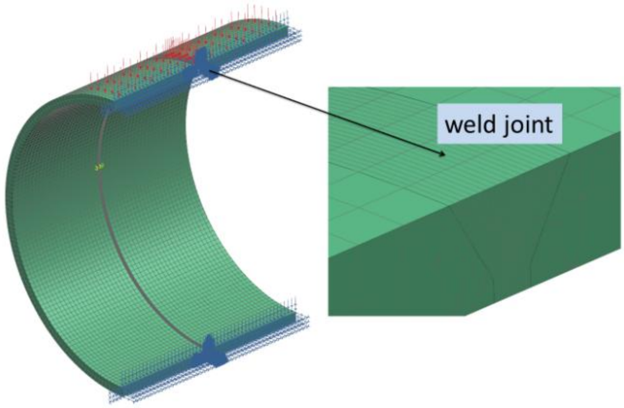


Fig. 9. The simplified model and boundary conditions of the strength analysis (the model with the weld joint)

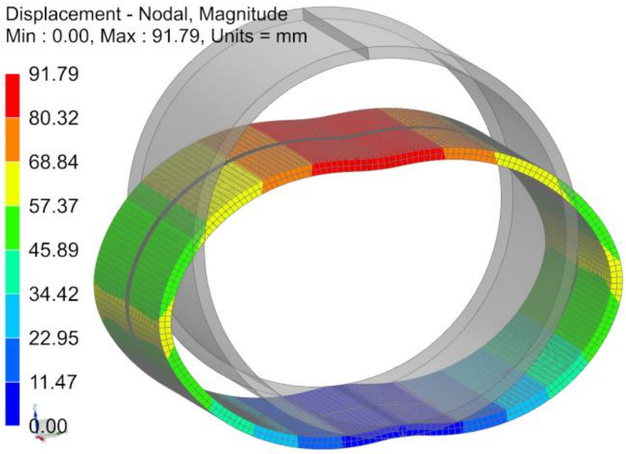


Fig. 10. The distribution of the displacement and the deformation in relation to the analysed model (the model with the weld joint)

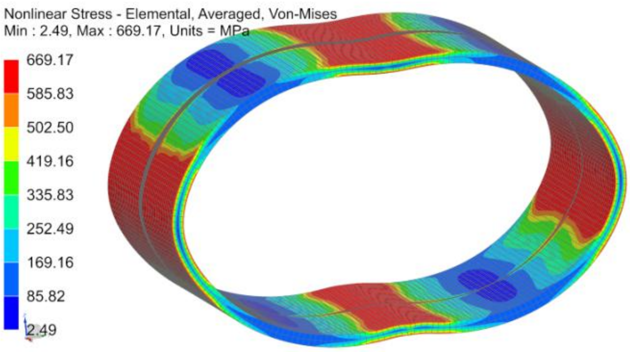


Fig. 11. The distribution of stress (Von-Mises) in the analysed model (the model with the weld joint)

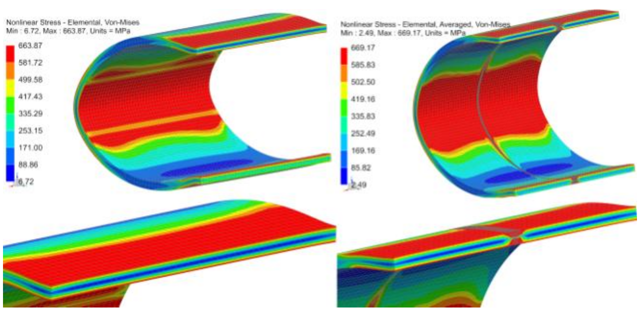


Fig. 12. The comparison of the distribution of the stress (Von-Mises) in the analysed model (a. the model without the weld joint, b. the model with the weld joint)

Based on the numerical analyses, it can be said that the maximum displacement of the compressed specimen without a weld joint is 106.7 mm, while in the case of the pipe with the weld joint is 91.9 mm. The obtained results are consistent with the measured displacements occurring in the specimen during experimental tests carried out on the hydraulic press (Table 1) in Huta Łabędy S.A. plant – producer of the tubes. In both cases, the assumed limit of strength of the pipe material, which is 700 MPa, was not exceeded.

3.2 Quasi-static loading experiments of the MMA, GMA, SSA and LASER+GMA welded joints

Quasi-static loading experiments of the MMA, GMA, SSA and LASER+GMA butt welded joints specimens were executed on tubes flattening press MECAMAQ - max load 40 tons (Figure 13). Results of welded joints flattening are shown in Figures 14 to 15, and Table 1.

Fig. 13. A view of tubes flattening press MECOMOQ

Fig. 14. A view of welded butt joints of API 5LX80, 323.9 mm diameter, 10 mm wall thickness tubes after flattening tests

Table 1. Results of welded butt joints of API 5LX80 323.9 mm diameter, 10 mm wall thickness tubes flattening tests

Specimen	H – mm	QUALITY
Parent material	226/214	no HF welded longitudinal weld cracks and tube edge cracks, acceptable per Huta Łabędy S.A. quality code*
MMA	226	no cracks of HAZ and weld metal and pipe edges
GMA	225	no cracks of HAZ and weld metal and pipe edges
SSAW	201	no cracks of HAZ and weld metal and pipe edges
LASER+GMA	155	no cracks of HAZ and weld metal and pipe edges

Remarks: Tubes flattening press MECAMAQ – max load 40 tons, flattening speed 0.40 mm/s, * - 226 mm – 70% of pipe diameter – no HF weld cracks, 214 mm – 66% of pipe diameter, no pipe edges cracks or tears

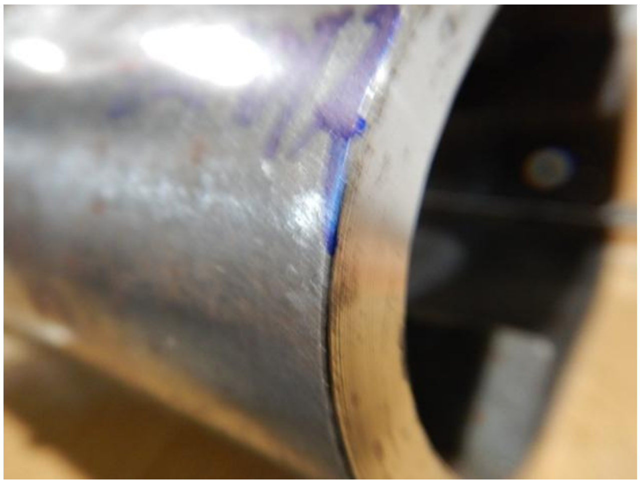


Fig. 15. A view of the pipe edge of most flattened welded joint of LASER+GMA – no tears and cracks

4. CONCLUSIONS

The FEM nonlinear analysis of the API 5LX80 pipe specimen 323.9 mm diameter and wall thickness 10 mm and the length of 240 mm and flattening experiments of catastrophic quasi-static indicated as follows:

-The identification of the parameters of the virtual FEM model allowed obtaining results comparable with those obtained from the real experiments. The matched FEM model can be used for numerical analyses for more expanded pipe systems and various boundary conditions.

-All flattening tested specimens of MMA, GMA, SSA and Laser+GMA welded joints specimens proved high quality, not lower than base material of the API 5LX80 pipe.

Acknowledgments

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5. REFERENCES

1. Abboudi, A., Chermime, B., Boulahrouz, S., (2018). *Simulation of the flattening of high frequency induction welded tubes*, Mechanics and Mechanical Engineering, **22**(1), 273-284.
2. Abduh M., (2009). *Erosion Corrosion – Learning from Humber Estuary*, Available from: https://abduh137.wordpress.com/category/engineering-failures/, Accesed: 11/05/2020.
3. ASTM 370, 2019 - Standard Test Methods and Definitions for Mechanical Testing of Steel Products.
4. Brickstad, B., Schimpfke T., *Benchmarking of structural reliability models for risk analyses of piping*, Swedish Nuclear Power Inspectorate (SKI), SE-106 58 Stockholm, Sweden. Gesellschaft für Anlagen und Reaktorsicherheit (GRS) mbH, D-50667 Köln, Germany. Available from: https://pdfs.semanticscholar.org/dc95/7098e3047f8fb6c030fc3a9df0fceeef4fef.pdf?_ga=2.142886710.2063904234.1598616093-209817455.1598616093, Accesed: 11/05/2020.
5. CSB investigations involving inadequate mechanical integrity programs. Chevron Refinery Fire, Chevron U.S.A. Inc. Refinery in Richmond, California. U.S. Chemical Safety Board. Available from: https://www.csb.gov/recommendations/csb-investigations-mechanical-integrity/, Accesed: 11/05/2020.
6. EN ISO 8492:2004, *Metallic materials - Tube - Flattening test*.
7. Hannachi Med Tahar, H., Djebaili, B., (2015). *Analysis of Control by Flattening of the Welded Tube*, World Academy of Science, Engineering and Technology International Journal of Materials and Metallurgical Engineering, **9**(11), 1324-1328.
8. https://www.statista.com/statistics/981799/largest-oil-refineries-worldwide/, Accesed: 11/05/2020.
9. https://www.listnbest.com/11-worlds-largest-oil-refineries-processing-capacity/, Accesed: 11/05/2020.
10. Mill test certificate NO 160818. POSCO. HUTA ŁABĘDY S.A. POLAND, Gliwice.
11. Paolicci, F., Reza, S., Bursi, O., Rfcs - induse project: *Structural Safety of Industrial Steel Tanks, Pressure Vessels and Piping Systems Under Seismic Loading*, Grant No. RFSR-CT2009-00022, Available from: https://op.europa.eu/en/publication-detail/-/publication/dfb8b89c-8de0-435c-b262-9acec59f318d, Accesed: 11/05/2020.
12. Rintamaa, R., (1989). *Prevention QF catastrophic failure in pressure vessels and pipings*, Final Report of the NKA-Project MAT 570. Nordic liaison committee for atomic energy.
13. Simonen, F., A., (2010). *Pressure vessels and piping systems: reliability, risk and safety assessment. Ancillary equipment and electrical equipment*, Pacific Northwest National Laboratory, Richland, Washington USA, I, Available from: http://www.desware.net/sample-chapters/d09/e6-165-07-00.pdf, Accesed: 11/05/2020.
14. Vicente, F., (2014). *Criticality assessment of piping systems for oil & gas facilities*, Featured Article by ABB, **20**(3), 15-18.

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