CONTRIBUTION TO MECHANICAL PROPERTIES ASSESSMENT OF SPHERICAL CYLINDRICAL HEAD SHELLS MADE BY THE INCREMENTAL SHEET FORMING

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ABSTRACT
The paper describes the determination of the mechanical properties of the spherical floors of pressure vessels, obtained by the welding process and shaped by the process of gradual local deformation in the cold state, i.e. by the process of Incremental sheet forming (ISF). Spherical cylindrical bottoms are an integral part of most closed-pressure vessels. Cylindrical pressure vessel floors are made from one part, but the standards also allow for welded construction when the dimensions of the floors are larger than the standard dimensions of the sheet metal for production. Pressure vessel floors obtained by the welding process and shaped by the process of gradual local deformation in the cold state, i.e. by the process of incremental deformation, have a multiaxial initial stress state, which differs significantly from the initial stress state of the cylindrical part of the vessel.
Checking the behavior of such floors before completing the vessel itself, i.e. before putting it into operation, is necessary, on the one hand, due to a large number of influencing factors, and on the other hand, due to the high cost of testing the real construction itself.
The aim of the test is to determine the influence of the parameter: type of material, thickness, and diameter on the following quantities: mechanical properties, R_{eH}, R_m, A_5, and total energy used for impact, KV.

1. INTRODUCTION

The floors of pressure vessels are exposed to a complex stress state (the appearance of tensile and bending stresses), which differs from the stress states of the cylindrical part of the pressure vessel, and therefore the considerations related to the cylindrical part of the vessels cannot be explicitly mapped to the behavior and integrity of the floors. On the other hand, in the case of large pressure vessels, the floors are very often made from large starting pieces (sheets) whose dimensions exceed the standard commercial dimensions, and it is necessary to form the starting pieces by welding procedures, which further impairs the integrity of the starting material.
The welded joint as a complex and heterogeneous structure represents a critical place in the welded construction. Therefore, in most cases, the safety of a welded structure is evaluated

based on the properties of the welded joint as a whole, and the properties of all its constituent parts. In many cases, the behavior of the welded joint as a whole differs from the behavior of the weld metal, the heat-affected zone (HAZ), and the base metal. The European directive for pressure equipment 97/23/EC [1] should ensure the operational safety of pressure equipment with specifics in design, construction, and testing. An alternative is the testing of samples taken from the structure itself before installation, i.e. simulating the behavior of the floors during exploitation using plate test tubes. The procedure of metal processing by gradual deformation using the mechanical action of an indenter is relatively insufficiently researched, especially in the field of integrity assessment as a multidisciplinary approach.

A good part of the previous research was focused on the optimization of technology and the development of machines for this purpose because there are a large number of applications of the products obtained by this method, especially parts made of steel sheets. Individual parts are installed in responsible machine structures and must meet the strict requirements that treat such products, which certainly include pressure vessels. The process of making the wedges by incremental deformation together with rolling around the circumference, to pull out the cylindrical part of the wedge, additionally complicates the state of stress due to the presence of high local pressure.

This approach to analysis enables obtaining the data necessary for a reliable assessment of the head properties, defining the parameters of choices and decisions, and determining the cause of bad behavior aimed at the correction and improvement of the manufacturing technology.

This paper contributes to the evaluation of the mechanical properties of cylindrical floors made by the ISF forming process.

2. TECHNOLOGY OF MANUFACTURING SPHERICAL FLOORS BY INCREMENTAL DEFORMATION

The process of forming by incremental deformation is the process of forming metal by progressive local deformation - incremental sheet forming (ISF). In the ISF procedure, the tool is moved along the contour of the workpiece, creating small deformations in the material, which gradually shape it into the desired shape. This method of manufacturing requires low production costs, and low tool costs and represents a potentially attractive solution for flexible production.

The construction technology must be designed based on all relevant influences to ensure that the floors are safe during working life. Allowable stresses for pressure equipment must be limited by possible errors in operating conditions, to eliminate the uncertainty arising from manufacturing, calculation models, actual operating conditions, and material characteristics and behavior. The incremental deformation of the roundel is performed on a hydraulic press with an exchangeable tool and pressure force. The final shaping of the torus was done on a press type P2MF 200x4 – Sertom, Milan, Figure 1 [2].

Figure 1. Production of floors by incremental deformation process [2]

Floors for experimental research are made by gradual pressing from initial preparations, the so-called rounds, obtained from welded sheets. During such a process of making floors, pressure zones are observed along the radius as a consequence of the manufacturing technology with a combination of welding and plastic deformation. Floors made for experimental research have a large number of segments that are radially welded. Welded joints are stiffer and thicker than the base material, thus preventing the material from stretching and causing the appearance of waviness at the edges.

Earlier research and experience in application [3] showed that the most commonly used material for making floors is hot-rolled carbon steel sheet in the range of 200 to 800 N/mm^2. These steels have good plasticity properties and the production speed depends on the thickness of the material and the magnitude of the tensile strength for the same shape and size. Also, it was observed that with these materials, the waviness at the edges is smaller with thicker materials.

3. EXPERIMENTAL RESEARCH

The mechanical tests presented in this paper are aimed at obtaining a more complete picture of the state of the material of spherical pressure vessel floors, made by welding from several segments. The floors are made of two different materials, S235JR and P460NL1, in two thicknesses (6 mm and 15 mm) for a specific diameter (1500 mm).

Chemical composition from quality S235JR and P460NL1 according to the standard EN 10028-3:2017, is given in Table 1 [2].

Table 1. Chemical composition from quality S235JR and P460NL1 [2]

Chemical composition of the base material, %											
steel grade	C	Si	Mn	P	S	Al	Cr	Ni	Mo	Cu	C_{EV}
S235JR, #6 mm	0,13	0,22	0,41	0,012	0,009	0,037	0,016	0,10	0,001	0,32	0,25
S235JR, #15 mm	0,13	0,22	0,40	0,012	0,006	0,036	0,016	0,12	0,001	0,35	0,26
P460NL1, #6 mm	0,17	0,40	1,55	0,010	0,003	0,028	0,04	0,04	0,004	0,02	0,47
P460NL1, #15 mm	0,18	0,56	1,67	0,016	0,003	0,032	0,04	0,52	0,003	0,04	0,52

In addition to the known influential parameters on the production of pressure vessel floors by the incremental deformation process, the behavior of floors with a welded joint remains unknown.

The welding technology in accordance with EN ISO 4063 is 121 (EPP/LP). Welding was performed with protective powder, preheating temperature 180 ^{0}C, weld width 15-17 KJ/cm for 6 mm thick sheets and 27-44 KJ/cm for 15 mm thick sheets.
The aim of the investigation is to determine the influence of the parameters: type of material, thickness, and diameter on the following mechanical properties, R_{eH}, R_m, A_5, and total energy used for impact, KV. The mechanical properties of the base material are given in Table 2.

Table 2. The mechanical properties of the base material [2]

Base material	Mechanical properties of the base material									
	R_{eH}, MPa		$R_{p0,2}$, MPa		R_m, MPa		A_5		KV, J	
	min.	max.	min.	max.	min.	max.	min.	max.	min.	max.
S234JR+N 6 mm	345	366	-	-	456	488	32,9	33,3	-	-
S234JR+N 15 mm	330	350	-	-	455	485	32,1	32,1	-	-
P 460 NL1 NT 6 mm	469	493	-	-	515	595	28	34	-	-
P 460 NL1 NT 15 mm	466	474	371	380	608	620	24,2	29,2	-	-

Regard to the defined problem of this specific structure (pressure vessel), primarily refers to the process of making the bottom of the vessel (processing by plastic deformation) as well as the procedure of preliminary welding to achieve the desired diameter, the experimental part of the research is carried out on series of test tubes taken from the floor of the vessel. The samples were taken from the initial welded sheets before any applied technology (series I), then from the finished floors produced by plastic deformation (series II).
The samples for the conducted tests are standard test tubes that in some cases are modified (adjusted) to obtain the most accurate results. The focus of the test is the heat-affected zone as potentially the most critical place from the aspect of safety as well as quality control possibilities. Destructive tests refer to the definition of material properties by destructive tests on test tubes according to current standards, that is, the determination of parameters used in the assessment of the safety and integrity of the analyzed material.

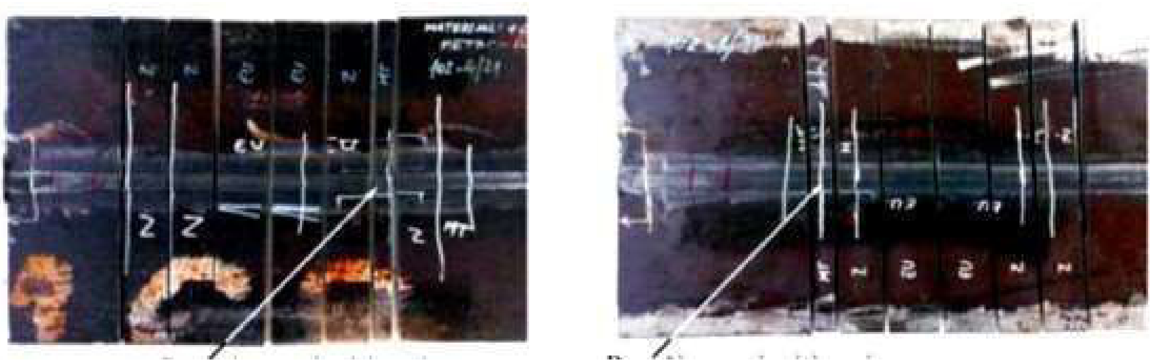
3.1 Scheme of sample extraction

Floors for experimental research were made using the plastic incremental deformation process. The initial preparation for making the floor is a circular sheet of tin, the so-called. roundels. For the experiment, two roundels of different dimensions were made: ϕ1500x6 mm and ϕ1500x15 mm. Samples were made in two sets (series):

- Ist set samples from the starting sheet,
- IInd set is sheet metal samples after plastic deformation.

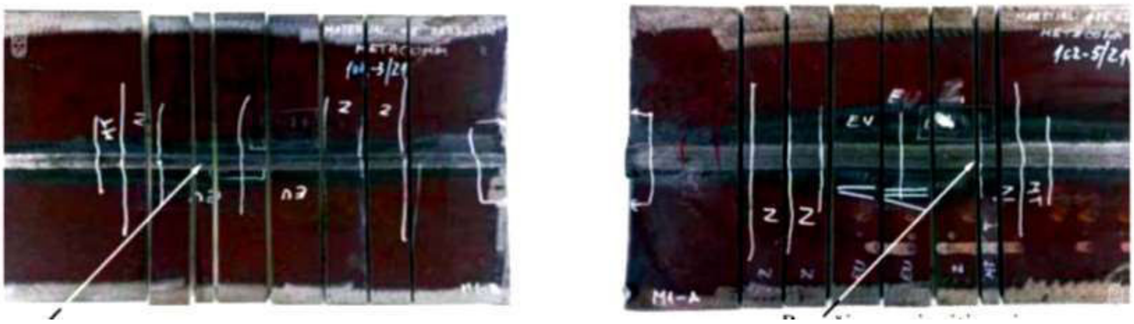
To assess the impact of the weakest place, i.e. heat-affected zone, after plastic deformation, the test tubes were taken from the direction transverse to the longitudinal axis of the welded joint, Figure 3, Figure 4, and Figure 5.

Figure 3. Taking samples from the manufactured floor



test surface, the thickness of 6 mm test surface, the thickness of 15 mm

Figure 4. Location of taking samples of sheet P460NL1 NT



test surface, the thickness of 6 mm test surface, the thickness of 15 mm

Figure 5. Location of taking samples of sheet S235JR+N

3.2 Determination of tensile properties

Tensile tests of test tubes removed from the bottom of the pressure vessel were performed at room temperature +18 °C. The test was performed on a universal hydraulic machine for static tests AMSLER, ser. No. 599/625.

The test procedure itself is defined by the standard BAS EN ISO 6892-1:2017 B [4], on test tubes for tensile tests whose geometry is given by the standard BAS EN ISO 4136:2014 [5]. The test tubes were modified with an incised transverse groove in the heat-affected zone, which is the subject of the study, Figure 6.

The tests were carried out for two series of samples and materials of the M1 and M2 designations.

Figure 6. Test tubes for the determination of tensile properties - series II

A typical layout of the tensile test diagram for the test tube of series I (sheet 15 mm, material M1) is given in Figure 7, and for series II (sheet 15 mm, material M2) in Figure 8. The results of tensile tests of the test tubes for the two series are given in Table 3 and Table 4.

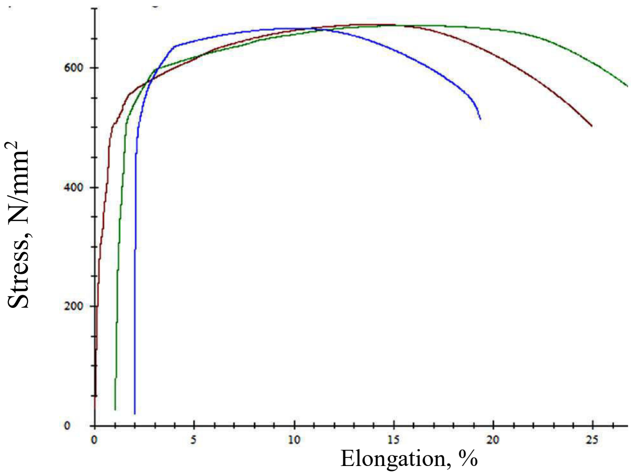


Figure 7. Stress-elongation diagram of series I test tubes

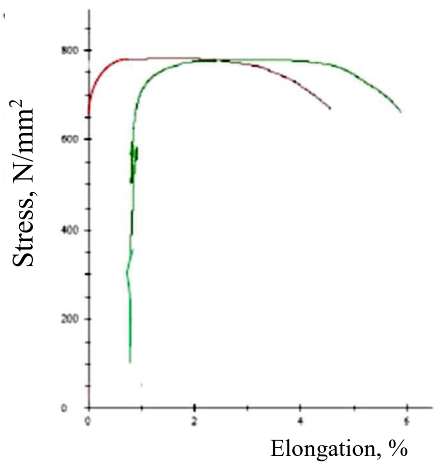


Figure 8. Stress-elongation diagram of series II test tubes

Table 3. Tensile test results of test tubes from series I for two materials

Material	S235JR+N (M1) ϕ1500 mm		P460 NL1 (M2) ϕ1500 mm	
Thickness	6 mm (M1-B)	15 mm (M1-A)	6 mm (M2-D)	15 mm (M2-C)
R_{eH}, MPa	344	340	407	531
R_m, MPa	465	475	593	670
A_5 (%)	27,33	34,0	20,83	31,6

Table 4. Tensile test results of test tubes from series II for two materials

Material	S235JR+N (M1) ϕ1500 mm		P460 NL1 (M2) ϕ1500 mm	
Thickness	6 mm (M1-B)	15 mm (M1-A)	6 mm (M2-D)	15mm (M2-C)
R_{eH}, MPa	534	612	614	763
R_m, MPa	597	637	682	780
A_5 (%)	9,75	10,75	9,5	11,75

Analyzing the results of the tensile test given in Table 3 and Table 4, it can be stated that the results are within the limits of the values for the analyzed materials after welding – series I and after plastic deformation – series II. The characteristic of the curve corresponds to a ductile material.
The values of the mechanical properties on the samples from series II (samples from the floors after plastic deformation) are above the values in the base material, Table 4, except for the ductile properties. Plastic deformation led to the strengthening of the material and an increase in the values of yield stress and tensile strength. At the same time, a decrease in ductile properties, i.e. a decrease in material elongation, was observed. Fracture took place in a controlled manner in the heat-affected zone. This indicates that it is about "overmatching", that is, that the mechanical properties of the strength are better in the heat-affected zone than in the base material.

3.3 Determining the impact energy of fracture

Determining the work required for fracture under established test conditions is most often used for ongoing control of the quality and homogeneity of the material, as well as its processing. This test procedure can determine the tendency to brittle fracture, that is, the tendency to increase brittleness during the exploitation (aging).
Impact tests of the samples were performed on a 300 J Charpie pendulum at a room temperature of +20 °C. The test procedure itself was carried out according to ISO 148-1:2017 [6] on standard test tubes (BAS EN ISO 9016:2012, [7]) whose layout is given in Figure 9.

Figure 9. Shape and dimensions of a standard test tube with a V notch for testing by the Charpie method

The test obtained the results of the total energy expended on impact. The test results of the impact properties of test tubes are given in Table 5 and Table 6.

Table 5. Test results of test tubes from series I for two materials (notch in the HAZ)

Material	S235JR+N (M1) ϕ1500 mm		P460 NL1 (M2) ϕ1500 mm	
Thickness	6 mm (M1-B)	15 mm (M1-A)	6 mm (M2-D)	15 mm (M2-C)
KV, J	52- welded joint	56- welded joint	47- welded joint	75- welded joint
	53-HAZ	87-HAZ	35-HAZ	48-HAZ

Table 6. Test results of test tubes from series II for two materials (notch in the HAZ)

Material	S235JR+N (M1) ϕ1500 mm		P460 NL1 (M2) ϕ1500 mm	
Thickness	6 mm (M1-B)	15 mm (M1-A)	6 mm (M2-D)	15 mm (M2-C)
KV, J	45	103	15	41

The total energy spent on impact in the heat-affected zone of series II is reduced compared to series I. The effect of strengthening due to plastic deformation is the cause of the reduction in toughness.

4. CONCLUSIONS

Pressure vessels belong to one of the most complex and responsible machine constructions. The modern standard for pressure vessels EN 13445:2002 and the corresponding regulations for pressure equipment (PED) show all the seriousness with which the problem of vessels and other pressure equipment is approached in the developed world. Modern standards are constantly supplemented with new knowledge that is regularly checked and implemented in new versions of the standard. However, these regulations do not adequately cover floors made by incremental deformation, and the level to guarantee the complete safety of the construction is also questionable.

In the paper, various influencing parameters (materials S235JR and P460NL1, thickness 6 mm and 15 mm, for a specific diameter of 1500 mm) on the mechanical properties, R_{eH}, R_m, A_5, and the total energy used for the impact, KV, were analyzed. For these influential parameters, it is empirically assumed that they are the key technological parameters for the production of spherical pressure vessel floors, made by welding from several segments. The effect of the welded joint was observed without any geometric irregularity, that is, with the assumption that there are no unacceptable defects.

Analyzing the results of the tensile test given in Table 3 and Table 4, it can be stated that the results are within the limits of the values for the analyzed materials after welding – series I and after plastic deformation – series II. The characteristic of the curve corresponds to a ductile material.

The values of the mechanical properties of the samples from series II (samples from the floors after plastic deformation) are above the values in the base material. The plastic deformation led to the strengthening of the material and an increase in the values of the yield stress and tensile strength. At the same time, a decrease in ductile properties, i.e. a decrease in material elongation, was observed. The fracture occurred in a controlled manner in the heat-affected zone. This indicates that the mechanical properties of strength are better in the heat-affected zone than in the base material.

By examining the total energy spent on impact, it can be concluded that the total energy spent on impact in the heat-affected zone of series II is reduced compared to series I. The strengthening effect due to plastic deformation is the cause of the reduction in toughness.

Floors made by the process of incremental deformation of welded starting pieces as an integral part of closed pressure vessels have met the requirements of the standards defining pressure vessels and guaranteeing the safety of these responsible constructions.

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