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INVESTIGATION OF RESIDUAL STRESSES AND STRAIN IN HIGH FREQUENCY LONGITUDINAL WELDED PIPES

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Abstract: This paper presents results obtained via experimental measurements of residual stresses in the cross sections of longitudinal welded pipes. The experiment is carried out over following pipe dimensions: Ø 139,7×4 mm, Ø 139,7×7,72 mm, Ø 219,1×5 mm, Ø 219,1×8 mm, Ø 244,5×8.94 mm, Ø 323.9×7,10 mm and Ø 323,9×10 mm. Residual stresses are measured with strain gages set upon the outside wall of the pipes. The results received from the gages show considering amount of stress captured in the pipe wall because of cold plastic formation process. Residual stresses for different pipe dimensions are in the range of 70 up to 270 MPa.
Keywords: residual stresses, strain; longitudinal welded pipes; cold plastic formation; high frequency welding

1. INTRODUCTION

According the results from the experimental investigations, some stages from the production process can be separated as influential over the stress distribution in the final product.

Plastic formation process and welding modes play crucial role for defining the technology and the quality of the final product. Basic purpose of the plastic formation is achieving cylindrical shape of the steel sheet that has width equal to the pipe circumference. With longitudinal welding, forming of circumference is completed. Pipe shaping is continuous process. During material forming, material itself experiences elastic and plastic deformations that cause change in the mechanical properties like strengthening. Therefore, the material stress-strain distribution in the pipe cross section is changing significantly from the initial relaxed state.

In this paper it is investigated the influence of the plastic formation over the stress-strain distribution in pipe cross section and its influence in the mechanical properties of the final product.

Tests are conducted over pipes made of steel J55 API 5CT, H40 API 5CT and S235JRG2 welded with HF-ERW. Analysis with FEM gave model that most accurately describes the stress-strain distribution. Test samples are cut from random chosen pipes that are made in factory IMK- Ferizaj.

2. INFLUENCE OF PLASTIC FORMING ON RESIDUAL STRESS

The influence of plastic formation process can be observed in three separate cases given on Figure 1.

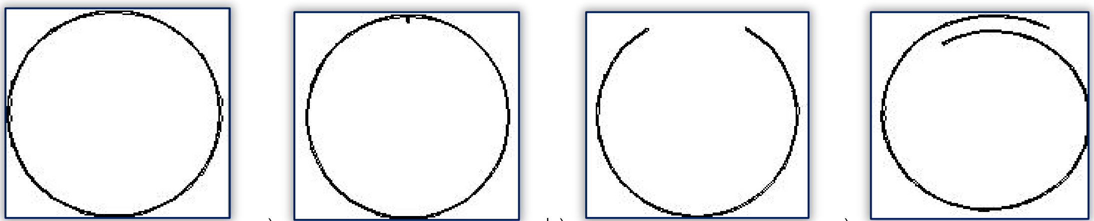
a) b) c) d)

Figure 1. The influence of plastic formation process
a) before cutting b) after cutting-without residual stress c) case with tension residual stress
d) case with compression residual stress

It is obvious that the level of plastic deformation during pipe forming is the most influencing factor. If plastic deformation is 100% and the gap between the ends is completely closed without any left elastic stress, then it is reasonable to expect that the level of residual stress will be at minimum or equal to zero Figure 1b) after applying longitudinal weld. In case when the plastic deformation is insufficient the ends will not close. The gap will stay open until additional amount of force is applied to overcome the tension residual stress trying to hold the pipe slit open Figure 1c).The case given on Figure 1d) shows example when after cutting the pipe, its ends create overlap because of compression residual stress. In practice most common case is the one on Figure 1c). Gap between the pipe ends varies depending on the technological process of manufacturing.

The relation between the level of residual stress and the gap can be expressed with the following equitation [1]:

$$\sigma = E \cdot t\left(\frac{1}{D_0} - \frac{1}{D_1}\right) \quad (1)$$

(1) Circumferential (hoop) stress in tube from change in diameter where and are the initial and final diameters, respectively Figure 2.

$$\sigma = E \cdot t\left[\frac{1}{D_0} - \frac{1}{\left(\frac{x}{\pi} + D_0\right)}\right] \quad (2)$$

$$\varepsilon = \frac{\sigma}{E} \quad (3)$$

Figure 2, shows Circumferential stress in tube from net opening displacement *x*.

3. EXPERIMENT CONCEPT - METHOD FOR MEASURING RESIDUAL STRESSES

For the experiment purposes, a method of saw cut ring samples from test pipes and slitting them on one side was performed. This is shown in Figure 3a and b.

After rings were slashed on one side, it was evident that they started to relax and create gap between the ends shown in Figure 1b. The gap varied according to the pipe dimensions, wall thickness, type of material and its strengthening level during the cold plastic formation process.

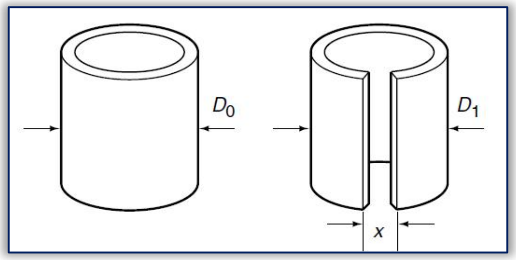

Figure 2. Determination of residual stresses in thin walled tube by deflection methods. Circumferential stress. t, thickness; D_0, initial diameter; D_1, diam. after slitting; x, net opening displacement.

Before starting the measurements of the stresses with strain gages, dimensions of the opened rings were once more precisely measured. Investigations were done with help of universal testing machine WPM ZDM10 shown on Figure 4. By increasing the force step by step, open rings were pressed until both ends touch each other and close the gap. Open ring is used as initial zero stress state. The difference between open and closed state of the ring is giving the residual stress captured inside the pipe Figure 5a and b. Location of the strain gage on the ring surface is shown on Figure 3c.

Figure 3a. Saw cut rings samples from pipe products

Figure 3b. Slitting pipe rings from one side

Figure 3c. Location of the strain gage on rings surface

The experiment was done at the Faculty of Mechanical Engineering in Skopje, Laboratory for testing materials. It is important to notice that in order to isolate the influence of residual stresses caused by welding, several experiments were done where pipe ring was sliced opposite on the weld side. The deformation was the same as if the ring was sliced in the weld length. This clearly shows that the heat treatment applied on the weld after pipe is welded is restoring heat affected zone to initial relaxed state.

Figure 4. Universal testing machine WPM ZDM10

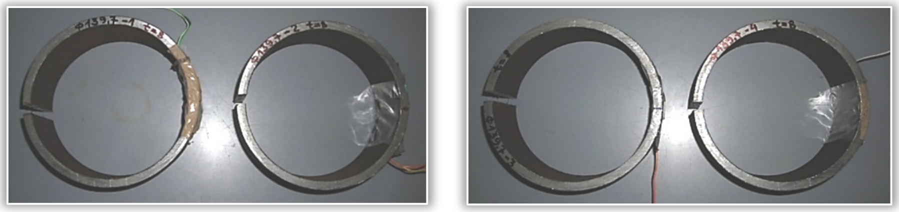

Figure 5a. Rings before force is applied

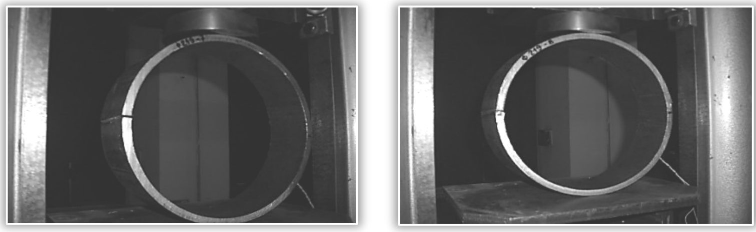

Figure 5b. Ring after force is applied to cause gap closing

Sample No. 1

Material quality	J-55, H40, E = 2x10^5 [MPa]							
Production standard	Ø 139.7×7.72 mm				Ø 244.5×8.94 mm			
Number of rings	1V	2V	3M	4M	1V	2M	3V	4M
D_o[mm]	140.45	140.55	140.50	139.7	246.65	246.65	244.70	246.65
D_1[mm]	142.52	142.25	142.26	141.41	249.73	251	247.42	251
P_o[mm]	442	443	442	443	776	776	769.82	776
P_1[mm]	448.38	447.53	447.57	444.89	785.66	789.89	778.38	790
t [mm]	8.00	7.99	8.00	7.99	9.35	9.45	9.42	9.42
b [mm]	61	60	60	61	61	58	61	61
Openings [mm]	6.53	5.36	5.56	5.40	9.66	13.93	8.56	14.03
ε [$\mu\varepsilon$]	827	785	704.43	692	467.53	472.5	423	661.88
σ [*MPa*]	168.55	160	143.52	141	93.50	94.50	84.64	132.37
Average value ε =752 [$\mu\varepsilon$]					Average value ε = 506 [$\mu\varepsilon$]			
Average value σ =153 [*MPa*]					Average value σ = 101 [*MPa*]			

Sample No.2

Material quality	S 235 JRG2, RST 37-2, E = 2x10^5 [MPa]							
Production Standard	EN 10025, DIN 17100							
Standard Dimensions	Ø 323.9×7.10 [mm]				Ø 323.9×10 [mm]			
Number of rings	1M	2M	3V	4V	5V	6V	7M	8M
D_o[mm]	323.25	323.8	323.55	323.85	323.65	323.55	323.55	323.55
D_1[mm]	328.92	329.32	328.49	328.77	329.76	328.62	327.82	328.96
P_o[mm]	1017	1020	1017	1018	1020	1018	1018	1018
P_1[mm]	1034.8	1036	1033.4	1034.3	1037.4	1033.8	1031.3	1034.9
t [mm]	7.7	7.47	7.07	6.99	10.33	10.37	10.35	10.45
b [mm]	63.7	71	69	66.2	60	60	60	60
Openings [mm]	17.80	16.06	16.43	16.33	17.43	15.86	13.33	16.93
ε [$\mu\varepsilon$]	410	386.6	328.61	323	591.58	484.58	416.66	531.16
σ [*MPa*]	82	77.33	65.72	64.60	118.27	96.91	83.33	106.23
Average value ε = 362 [$\mu\varepsilon$]					Average value ε = 506 [$\mu\varepsilon$]			
Average value σ = 72 [*MPa*]					Average value σ = 101 [*MPa*]			

Sample No.3

Material quality	S 235 JRG2, RST 37-2, E = 2x10^5 [MPa]							
Production Standard	EN 10025, DIN 17100							
Standard Dimensions	Ø 219.1×5 [mm]				Ø 219.1×8 [mm]			
Number of rings	1M	2M	3V	4V	5V	6V	7M	4M
D_0[mm]	221.70	220	220.50	220.50	220.15	220.20	220.20	220
D_1[mm]	224.70	222.91	222.90	223.13	221.29	221.46	221.54	221.53
P_0[mm]	697.46	692.12	693.69	693.69	692.59	692.74	692.74	692.12
P_1[mm]	706.92	701.28	701.25	701.99	696.19	696.74	696.97	696
t [mm]	5.32	5.42	5.10	5.17	8.07	8.17	8.12	8.20
b [mm]	60	60	61	61	62	60	61	60
Openings [mm]	9.46	9.16	7.56	8.30	3.60	4.00	4.23	3.90
ε [$\mu\varepsilon$]	320	322	250	277.50	190	213	224	209
σ [MPa]	64	64.45	50	55.50	38	42.65	44.8	41.80
Average value ε = 292 [$\mu\varepsilon$]					Average value ε = 209 [$\mu\varepsilon$]			
Average value σ = 58.5 [MPa]					Average value σ = 41.8 [MPa]			

Table 1. Measured residual stress in the ring samples

Ring designation	Ring wall thickness t (mm)	Diameter of open ring D (mm)	Strain Gages SG	Force for closing the open ring (N)	Gap (mm)	Stress (Mpa)	Width of the ring section
139.7 - 1M	4.0	142.3	798	343	6.9	159.6	60.5
139.7 - 2M	3.8	141.6	836	294	7.7	167.2	60.0
139.7 - 3V	4.1	143.2	1369	588	9.7	273.8	61.5
139.7 - 4V	3.7	143.0	1349	598	10.3	269.8	61.0
139.7 - 1V	8.0	142.5	1214	2746	6.5	242.8	61.0
139.7 - 2V	8.0	142.5	1131	2599	5.4	226.2	60.0
139.7 - 3M	8.0	142.2	1246	2599	5.6	249.2	60.0
139.7 - 4M	8.0	142.2	1163	2452	5.4	232.6	61.0
219.1 - 1M	5.3	224.7	538	255	9.5	107.6	60.0
219.1 - 2M	5.4	222.9	553	255	9.2	110.6	60.0
219.1 - 3V	5.1	222.9	474	245	7.6	94.8	61.0
219.1 - 4V	5.2	223.1	474	226	8.3	94.8	61.0
219.1 - 5V	8.1	221.3	354	549	3.6	70.8	62.0
219.1 - 6V	8.2	221.5	377	520	4.0	75.4	60.0
219.1 - 7M	8.1	221.5	429	549	4.2	85.8	61.0
219.1 - 8M	8.2	221.5	416	549	3.9	83.2	60.0
244.5 - 1V	9.4	250.0	705	1294	9.7	141.0	61.0
244.5 - 2M	9.5	251.0	1169	1814	14.0	233.8	58.0
244.5 - 3V	9.4	247.4	643	1177	8.6	128.6	61.0
244.5 - 4M	9.4	251.0	1141	1912	14.0	228.2	61.0
323.9 - 1M	7.7	329.0	652	392	17.8	130.4	63.7
323.9 - 2M	7.5	329.3	532	392	16.1	106.4	71.0
323.9 - 3V	7.1	328.5	499	392	16.4	99.8	69.0
323.9 - 4V	7.0	328.8	517	353	16.3	103.4	66.2
323.9 - 5V	10.3	329.8	816	1324	17.4	163.2	60.0
323.9 - 6V	10.4	328.6	760	1226	15.8	152.0	60.0
323.9 - 7M	10.3	327.8	712	981	13.3	142.4	60.0

4. CONCLUSIONS

As final conclusions following statements can be given regarding residual stresses in cold formed longitudinal welded pipes:

» The cross sections of the cold formed pipes contain captured stresses which are result of deformation and shaping of the plain sheet metal.
» This stresses can be measured and they are significant.
» Based on the results obtained from the theoretical and experimental work, the relation between residual stresses and level of deformation is clearly defined.
» The nature of the residual stresses is clearly from tension character which is easy to understand from opened rings.
» Residual stresses are in the range of 70 to 270 MPa which is shown in the Table 1.
» The presence of residual stresses can be from significant meaning for applications where pipes are used as constructive load bearing element, or pipes for drilling, which affects their strength.

- Residual stresses and deformations are larger in sections with smaller diameter opposite to bigger ones; first one experience more deformation that is causing deformation strengthening.
- The mechanical properties of the plain sheet metal before and after pipe formations are different for the longitudinal and transversal direction. Yield and UT Strength are bigger in the transversal direction than in longitudinal.
- It is clear that mechanical properties of the plain sheet metal before and after pipe formation are generally different. Yield and UT Strength is increasing in both transversal and longitudinal direction after formation process. Pipes that have smaller diameter have bigger Yield and UT Strength and smaller elongation than pipes with larger section. This is because of item 7.
- The purpose of this paper and its results is to contribute in the general knowledge for improving the technology and production process of cold formed pipes.

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