Latin American Journal of Solids and Structures
www.lajss.org

Development and Test of an Equipment to Measure Residual Strain Inside Pipes Using the Hole-Drilling Method

Abstract

Residual stresses are present in materials or structural component in the absence of external loads or changes in temperatures. The most common causes of residual stresses being present are the manufacturing or assembling processes. All manufacturing processes, such as casting, welding, machining, moulding, heat treatment, etc, introduces residual stresses into the manufactured object. The residual stresses effects could be beneficial or detrimental, depending on its distribution related to the component or structure, its load service and if they are compressive or tensile. In order to do the studies of residual stresses inside pipes, where the fatigue cracks normally initiate, an equipment that allows applying the Hole-Drilling Method was developed. The equipment efficacy was confirmed in this work by using it to detect residual strains inside a Mock-up that simulates the relief and security nozzle of Angra 1 Nuclear Power Plant (NPP) pressuriser.

Keywords

Residual stresses, hole-drilling method, measuring equipment, pressuriser security nozzle.

Luiz Leite da Silva [a]
Vladimir S. Ribeiro [b]
Denis H. Bianchi Scaldaferri [c]
Emerson Giovanni Rabello [d]
Wagner R. C. Campos [e]
Tanius R. Mansur [f]

[a] Centro de Desenvolvimento da Tecnologia Nuclear – CDTN/CNEN
Av. Presidente Antônio Carlos, 6627 – Campus UFMG – Pampulha, Belo Horizonte, MG, Brazil CEP 31.270901.
silall@cdtn.br
[b] Centro de Desenvolvimento da Tecnologia Nuclear da Comissão Nacional de Energia Nuclear – CDTN/CNEN
vladimirsoler@hotmail.com
[c] Centro de Desenvolvimento da Tecnologia Nuclear – CDTN/CNEN
dhbs@cdtn.br
[d] Centro de Desenvolvimento da Tecnologia Nuclear – CDTN/CNEN
egr@cdtn.br
[e] Centro de Desenvolvimento da Tecnologia Nuclear – CDTN/CNEN
wrcc@cdtn.br
[f] Centro de Desenvolvimento da Tecnologia Nuclear– CDTN/CNEN
tanius@cdtn.br

http://dx.doi.org/10.1590/1679-78253126

Received 30.05.2016
Accepted 21.06.2016
Available online 27.06.2016

1 INTRODUCTION

Residual stresses are present in materials or structural components even though external loads and changes in temperature do not exist. Residual stresses normally appear during manufacturing or assembling processes.

It is very common residual stresses appear after the cooling process of welded components, because materials have different thermal expansion coefficients. During the welding process, the material already deposited and cooled does not allow the subsequent melted material to contract, inducing tensile stresses on it.

Material phase transformations during the welding process induce residual stresses because of their volumetric change (for example austenite transforms into ferrite, bainite, pearlite or martensite). Therefore, the material in the melted zone and in the heat affected zone that are under phase transformation, try to expand and are constrained by the whole cool metal inducing residual stresses Rakin et al (2008), Withers and Bhadeshia (2001, part I), Withers and Bhadeshia (2001, part II), Francis (2007).

The residual stresses magnitude in the bead weld is related to the constraint level the mechanical structure could impose on it. In this case, the residual stress value may reach the metal yield limit. In components like pipelines and nozzles, the difference in diameters, wall thickness and materials used are great constraint factors to the final welded structure.

The residual stresses effects may be beneficial or detrimental depending mainly on their magnitude, if they are compressive or tensile and their distribution related to the structural component loads. Normally the residual stresses are detrimental and there are many documented cases where those stresses were the predominant structural failure factors ASTM E837- 13a (2013). In such cases the unknown residual stresses already present in the structure were added to the load stresses causing the failure. A particularly dangerous aspect of the residual stresses is that they are not noticed. Knowing the superficial residual stresses is important to predict structural failure when they are under working loads, mainly in corrosive environments when the problem is increased.

Nowadays the technique most used to measure residual stress is the Hole-Drilling Method. This is a semi destructive method and may be considered in some cases as non destructive ASTM E837-13a (2013). To perform this method, at first, appropriated strain gage rosettes are installed in the studied component surface. After that, a hole is drilled step by step at the geometric centre of the rosette. During the hole drilling, strains are detected close to it by the strain gage rosettes and the stresses are calculated based on those detected strains.

Applying the hole-drilling method inside pipes is not easy because of geometric limitations and difficulty in accessing the surface of interest. To overcome these problems the equipment shown in Figure 1 was designed and built. In this work, the equipment designed to help measuring residual stresses inside pipes was tested in a Mock-up that simulates the relief and security nozzle of Angra 1 NPP. The residual stresses in the Mock-up appeared mainly because of its dissimilar materials welding. Despite of the equipment had been developed for a specific inside diameter, it could be used in pipes with great range of inside diameters.

2 INSIDE PIPE RESIDUAL STRAIN MEASURING EQUIPMENT

A special equipment to measure strains in the inside surface of wall pipes using the technique of Hole-Drilling Method was designed and built. By means of characteristic shape, the equipment could be positioned concentrically with the inside pipe diameter. The equipment has mechanisms that allow positioning the drill exactly in the rosette centre. A web-cam connected to the equipment is used to align the drill with the rosette centre and to measure the hole diameter. The hole diameter is measured calibrating the webcam pictures with the diameter of the gage circle.

The drill is rotated by an air compressed turbine with rotation around 300,000rpm. Connected to the air compressed turbine there is a micrometer that allows the operator to control precisely the drill feed and the hole depth. The developed equipment is shown in Figure 1.

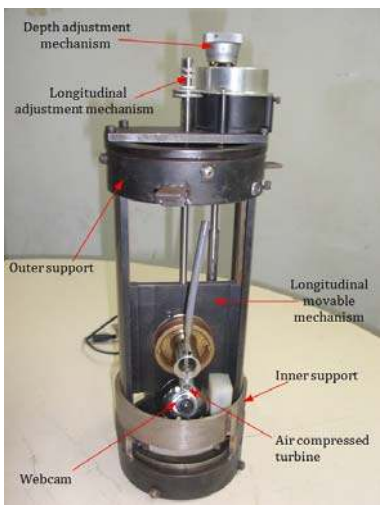


Figure 1: Developed equipment to assist measuring residual stresses inside wall pipes.

The webcam and the air compressed turbine are shown in Figure 2. The webcam is used to adjust the drill position in the strain gage rosette centre and to measure the hole diameter (Campos et al, 2013). The air compressed turbine is used to fasten and rotate the drill and then make the hole.

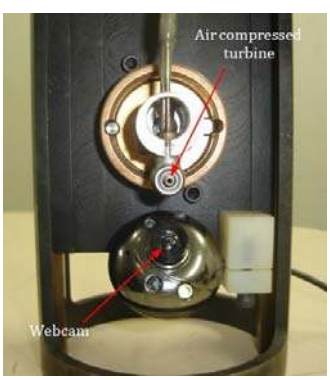


Figure 2: Webcam and the air compressed turbine

In Figure 3 the depth adjustment mechanism could be seen in detail. The mechanism is provided with a micrometer by means of each hole step could be precisely controlled. The mechanism to adjust longitudinally the drill position could be seen too in Figure 3. This mechanism has a screw shaft fixed in a small movable part that can move forward and backward, when the mechanism is turned.



Figure 3: Depth and longitudinal adjustment mechanisms

In Figure 4 the two supports could be seen. One of them is assembled in the equipment end that will stay inside the pipe. The other support is assembled along the equipment body and will touch the pipe flat surface to maintain the drill in the right position. The inside diameter of both supports are precisely adjusted to the equipment diameter. This adjust allows positioning correctly the drill in the strain gage rosette centre and make a precise hole.



Figure 4: Inner and outer supports and the developed equipment.

3 TEST METHODOLOGY

3.1 Mock-Up Used to Measure Inside Residual Strain

The mock-up was composed of three parts: a SA508 class 3 forged nozzle machined from a ferritic carbon steel plate with thickness of 130mm, an ASTM A276 F316L intermediate ring (safe end) machined from a forging disc with diameter of 220mm and wall thickness of 70mm, and an austenitic stainless steel pipe 316L schedule 160 with diameter of 168.2mm and 18.3mm of wall thickness. As could be seen, all these Mock-up parts were made of different metals and were welded using nickel alloys as filler material. The Mock-up fabrication process and its different materials induce residual stresses on it. Using the developed equipment these residual stresses were measured inside the Mock-up using the Hole Drilling Method. The Mock-up that simulates the relief and security nozzle of Angra 1 NPP pressuriser could be seen in Figure 5.



Figure 5: Mock-up that simulates Angra 1 NPP nozzle.

3.2 Strain Gage Arrayed Inside the Mock-Up

The circumference of the inside Mock-up diameter was divided by three radial lines in order to position the studied points. One of these lines is defined as the origin and was nominated as 0^0. A second line was positioned 120^0 clockwise from the origin line ($+120^0$). A third line was positioned 120^0 counter clockwise from the origin line (-120^0). Figure 6 shows these division lines and the strain gages positions could be seen in Table 1.



Figure 6: Strain gage positioning lines inside the Mock-up.

Point		Material	Location (mm)	SG1 Orientation
I 1	I1	316L	87 (Tube)	longitudinal
I 2	I1-120	316L	92 (Tube)	circumferential
I 3	I0-120	316L	52 (Tube)	longitudinal
I 4	I3-120	316L forged	146 (Safe End)	circumferential
I 5	I3+120	316L forged	153 (Safe End)	circumferential
I 6	I4	A-508	190 (Nozzle)	longitudinal
I 7	I4-120	A-508	191 (Nozzle)	circumferential
I 8	I4+120	A-508	195 (Nozzle)	circumferential
I 9	I5	Inconel 182	165 (Weld)	longitudinal
I 10	I5'	Inconel 182	175 (Weld)	longitudinal
I 11	I7	A-508	264 (Nozzle)	longitudinal
I 12	I7-120	A-508	264 (Nozzle)	longitudinal
I 13	I7+120	A-508	264 (Nozzle)	longitudinal

Table 1: Positions of studied points in the Mock-up and the respective materials.

3.3 Performing the Hole-Drilling Method

The hole-drilling method was used to measure the residual stresses in the Mock-up inside wall. In this method, appropriate rosettes to detect residual strain must be used. In this work rosettes of type A were used and a picture of one of them could be seen in Figure 7 ASTM E837- 13a (2013). The rosettes were installed in the inside component surface and then small and shallow hole is drilled in the rosette centre. The hole is drilled step by step and the strain changes in its neighbourhood were detected by the strain gages rosette. Using these measured strains the residual stresses could be calculated. The relief strains or the changes in strain are calculated using Equation (1) (Tec Note TN-503, 2010).

$$\varepsilon = \frac{\Delta R / R}{K} \tag{1}$$

In Equation (1) ε is the measured strain, $\Delta R = R_f - R_i$ (Ohm) for each drilled step; R_i is the strain gage resistance value before begin drilling the hole and R_f is the strain gage resistance value for each drilled step and K is the gage factor. The principal residual stresses are calculated by Equations (2) and (3). The constants $\bar{A}$ and $\bar{B}$ are conform Tech Note TN-503 (2010). The principal strain orientation related to the ε_1 is done by Equation (6).

$$\sigma_{\max} = \frac{\varepsilon_1 + \varepsilon_3}{4\bar{A}} - \frac{1}{4\bar{B}}\sqrt{(\varepsilon_3 - \varepsilon_1)^2 + (\varepsilon_3 + \varepsilon_1 - 2\varepsilon_2)^2} \tag{2}$$

$$\sigma_{\min} = \frac{\varepsilon_1 + \varepsilon_3}{4\bar{A}} + \frac{1}{4\bar{B}}\sqrt{(\varepsilon_3 - \varepsilon_1)^2 + (\varepsilon_3 + \varepsilon_1 - 2\varepsilon_2)^2} \tag{3}$$

$$\overline{A} = -\frac{1+\mu}{2E}\overline{a} \tag{4}$$

$$\overline{B} = -\frac{1+\mu}{2E}\overline{b} \tag{5}$$

$$tg2\alpha = \frac{\varepsilon_1 - 2\varepsilon_2 + \varepsilon_3}{\varepsilon_3 - \varepsilon_1} \tag{6}$$

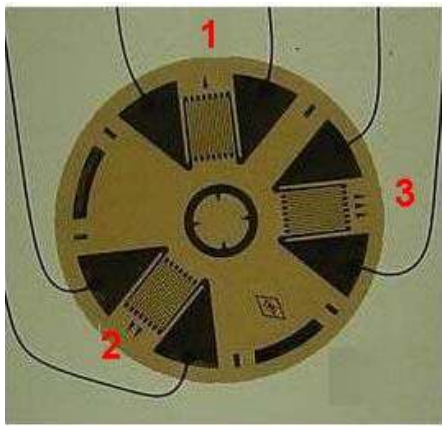


Figure 7: Typical rosette for residual stress (TML Pam E-101N, 2006).

The developed equipment mounted inside the Mock-up could be seen in Figure 8.

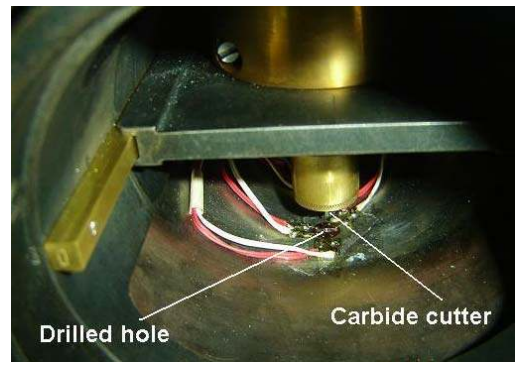


Figure 8: Developed equipment mounted inside the Mock-up.

Figure 9 shows a residual stress rosette attached in the inside wall Mock-up and the hole drilled in its centre. As could be seen in Figure 9a, the hole was made precisely in the strain gage rosette centre. Figure 9b shows the moment the hole was been drilled.



(a)



(b)

Figure 9: a) Rosette with the drilled hole; b) Drilling a hole in the inside wall Mock-up.

After calculating the relieved strains, it must be verified if the residual stresses field is uniform or non uniform. If the stresses field is uniform, the principal residual stresses values and their orientations are calculated following the recommendations contained in item 9 of the ASTM E837 - 13a code (2013) and in the manufacturer technical notes (Hoffmann, 1989, Tec Note-503, 2010). On the other hand, if the stresses field is non uniform, the residual stresses and its orientations are calculated following the item 10 in the ASTM E837- 13a (2013) code recommendations and in the manufacturer technical notes (Hoffmann, 1989, Tec Note-503, 2010).

The residual strains were measured using the materials and equipments listed below:

- Strain Gages: FRS-2-11 TML.
- Adhesive: Loctite 496.
- Protector Cover: Mcoat MM.
- Shielded Cables with 4 Wires: KMP/AF/Pirelli.
- Terminals: Kratos.
- Commutator and Data Acquisition Unit 34970A Model / Agilent.
- Multimeter PM2000 Model.

4 RESULTS

The inside residual strains were obtained in the thirteen measuring points indicated in Table 1. The residual stresses were calculated using these measured strains.

In order to compare the values of the Equivalents Uniforms Principal Residual Stresses with the tensile stress of the materials, the equivalent uniaxial stress was determined using Tresca and von Mises criteria.

Typical results obtained during the measuring process and from the data processing are shown in Tables 2 and 3 and in Figure 10. In Figure 10 could be seen the normalized relieved strains from numerical examples of measuring point I3 + 120^{o}, compared with ASTM E837 – 13a (2013) uniform stress responses. The results shown in Table 3 are related to the measuring point I5'. In Table 2 the values of R1, R2 and R3 are the measured resistance of each strain gage rosette.

Depth		Strain Gages measurements		
Z (mm)	Z/D	R1 (ohms)	R2 (ohms)	R3 (ohms)
0.00	0.00	119.54	120.21	120.15
0.26	0.05	119.55	120.21	120.15
0.51	0.10	119.57	120.22	120.17
0.77	0.15	119.59	120.24	120.18
1.03	0.20	119.59	120.25	120.20
1.28	0.25	119.59	120.25	120.20
1.54	0.30	119.59	120.25	120.20
1.80	0.35	119.59	120.25	120.20
2.06	0.40	119.59	120.25	120.20

Table 2: Typical result for a measuring point, D is the drill diameter.

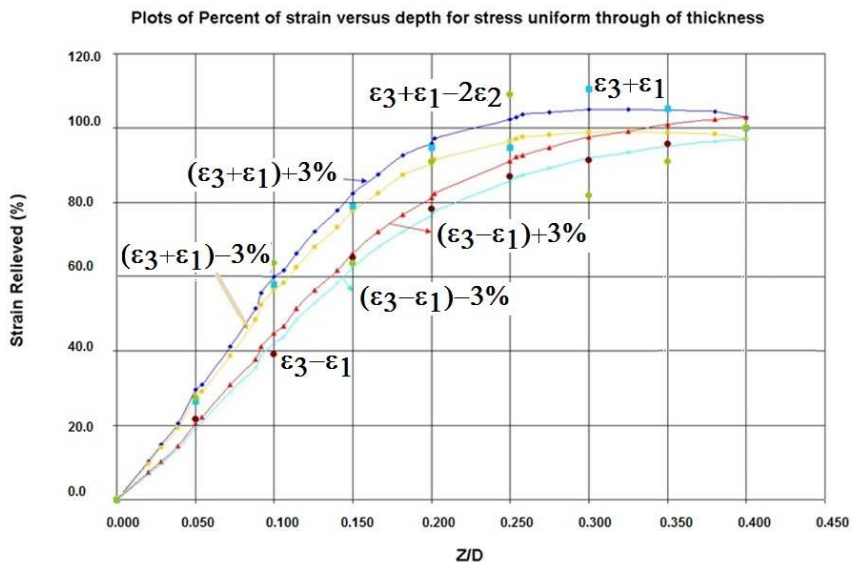


Figure 10: Normalized numerical relieved strains of point I3+120° compared using ASTM E837- 13a (2013).

Figure 11 shows the inside measured equivalents uniforms principal residual stresses in the 13 points. These points were positioned in all Mock-up materials. These values correspond to the measured strains when there was complete alleviation due to of the hole drilled at the rosette centre. The dashed lines correspond to the reliable limit of the Hole-Drilling Method, which is 70% of the yield stress of the material.

Depth		Measured strain (με)		Relieved strain			Coefficients A and B ($x10^{-6}$)				α(⁰)	Equivalent uniform principal stress (MPa)	
Z	Z/D			ε3+ε1	ε3-ε1	ε3+ε1-2ε2							
(mm)				(με)/%	(με)/%	(με)/%						σmin	σmax
		ε1	0	0	0	0	a		b				
0.000	0.00	ε2	0	/	/	/	A		B				
		ε3	0	0	0	0	4A		4B				
		ε1	40	56	-24	16	a	0.032	b	0.061			
0.260	0.05	ε2	20	/	/	/	A	-0.088	B	-0.126	73	-218	-102
		ε3	16	15	142	39	4A	-0.353	4B	-0.506			
		ε1	105	169	-41	49	a	0.071	b	0.140			
0.510	0.10	ε2	60	/	/	/	A	-0.193	B	-0.292	65	-274	-165
		ε3	64	45	238	118	4A	-0.773	4B	-1.167			
		ε1	166	294	-37	61	a	0.101	b	0.212			
0.770	0.15	ε2	117	/	/	/	A	-0.276	B	-0.442	61	-307	-226
		ε3	129	78	217	148	4A	-1.105	4B	-1.766			
		ε1	198	379	-17	41	a	0.120	b	0.266			
1.030	0.20	ε2	169	/	/	/	A	-0.328	B	-0.554	56	-309	-268
		ε3	181	100	100	100	4A	-1.313	4B	-2.217			
		ε1	198	379	-17	41	a	0.130	b	0.303			
1.280	0.25	ε2	169	/	/	/	A	-0.355	B	-0.630	56	-284	-249
		ε3	181	100	100	100	4A	-1.421	4B	-2.522			
		ε1	198	379	-17	41	a	0.134	b	0.325			
1.540	0.30	ε2	169	/	/	/	A	-0.365	B	-0.678	56	-276	-243
		ε3	181	100	100	100	4A	-1.460	4B	-2.711			
		ε1	198	379	-17	41	a	0.134	b	0.340			
1.800	0.35	ε2	169	/	/	/	A	-0.365	B	-0.708	56	-275	-244
		ε3	181	100	100	100	4A	-1.460	4B	-2.831			
		ε1	198	379	-17	41	a	0.132	b	0.346			
2.060	0.40	ε2	169	/	/	/	A	-0.359	B	-0.721	56	-279	-248
		ε3	181	100	100	100	4A	-1.436	4B	-2.886			

Table 3: Measurement of Residual Stresses by the Hole Drilling Strain Gage Method of point I5'.

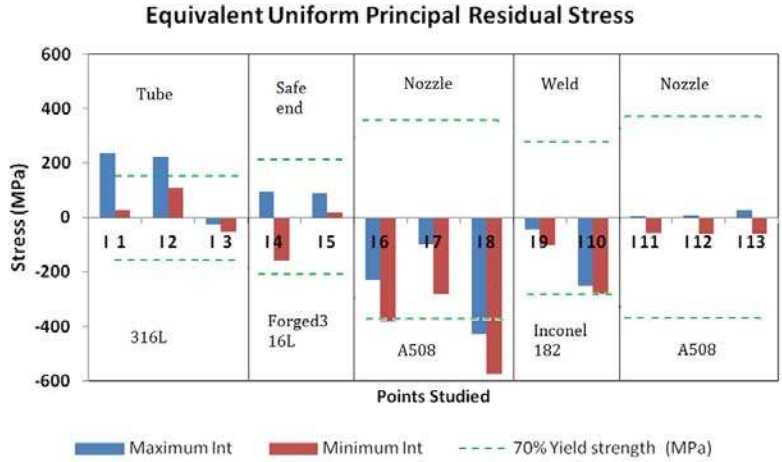


Figure 11: Equivalent uniform principal residual stress (MPa)

It could be observed that the inside residual stresses change in the direction from the pipe to the nozzle. At first there are relatively elevated tensile stresses in the pipe, what could be seen in results at positions I1, I2. Then the stresses change to compression in the safe-end and in the nozzle as could be seen from results at positions I4 and I13.

Near the heat affected zone, in the direction from the safe-end to the nozzle, there are high residual stresses in compression.

In some points the measured values were above the limit of 70% of the yield stress of the material. The comparison between the values using the Tresca and von Mises uniaxial criteria was proposed to evaluate this stress behaviour. In Figure 12, could be seen the results from Tresca and von Mises criteria.

Tresca and von Mises criteria showed that the residual stresses at the measuring points I1, I2, I4, I6 and I8 are beyond the limit of the Hole-Drilling Method. However the strains measured at those points could be considered as qualitative values for residual stresses studies.

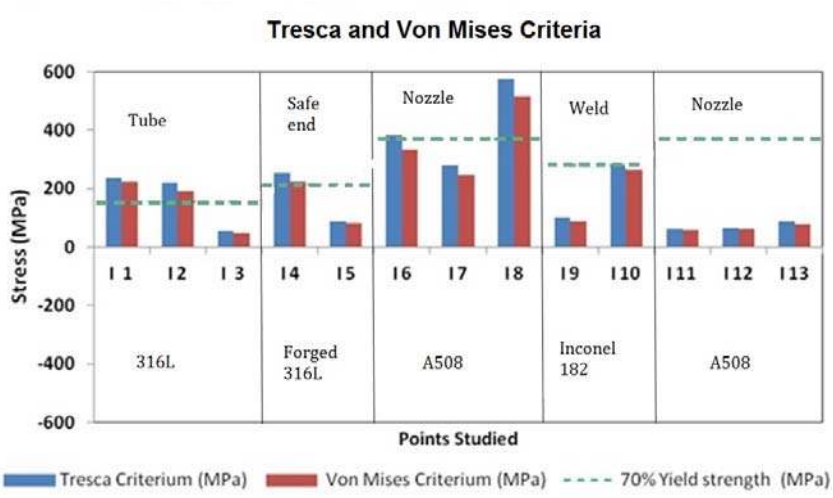


Figure 12: Tresca and von Mises criteria in Equivalent and Uniform Residual Principal Stresses.

5 CONCLUSIONS

It was possible determine the inside residual stresses in a Mock-up that simulates the security and relieve nozzle of the Angra 1 NPP, using the developed measuring equipment that allows applying the hole-drilling method inside pipes.

With the developed measuring equipment the drill could be precisely positioned at the strain gage rosette centre, the hole depth accurately controlled and the hole diameter correctly measured.

The residual stresses values obtained in the test of the measuring equipment are in accordance with Hole-Drilling Strain-Gage Method.

Many residual stresses in the Mock-up inside wall used to test the measuring equipment are in compression.

The residual stresses values exceeded 70% of the yield stress of the material in some measuring points of the Mock-up inside wall.

Acknowledgements

The authors would like to thank CDTN's staff of the Weld Laboratory and also the Stress Analysis Laboratory for their significant contribution to this work. The authors would like to thank also the institutions Fundação de Amparo à Pesquisa do Estado de Minas Gerais – FAPEMIG and Conselho Nacional de Desenvolvimento Científico e Tecnológico – CNPq for the financial support.

References

ASTM E 837-13a, Standard Test Method for Determining Residual Stresses by the Hole-Drilling Strain-Gage Method. October 2013.

Campos, W. R. C., Rabello E. G., Mansur, T. R., Scaldaferri, D. H. B., Paula, R. G. Souto, J. P. R. S. and Carvalho Júnior I. T., Residual Stress Measurements in the Dissimilar Metal Weld in Pressurizer Safety Nozzle of Nuclear Power Plant, International Nuclear Atlantic Conference - INAC 2013 Recife, PE, Brazil, November 24-29, 2013 Associação Brasileira de Energia Nuclear - ABEN ISBN: 978-85-99141-05-2 INAC 2013.

Francis, J. A., Bhadeshia, H. K. D. H. and Withers, P. J., "Welding Residual Stresses in Ferritic Power Plant Steels", Materials Sci. and Tech., Vol. 23 2007, pp. 1009-1020.

Hoffmann, Karl, "An Introduction to Measurements using Strain Gages. Publisher: Hottinger Baldwin Messtechnik GmbH, 1989.

Rakin, M., Gubeljak, N., Dobrojević, M. and Sedmak, A. Modelling of ductile fracture initiation in strength mismatched welded joint. Engineering Fracture Mechanics, 75(11), pp.3499–3510 (2008).

Tech Note TN-503, Measurement of Residual Stresses by the Hole-Drilling Strain Gage Method. Vishay Micro-Measurements, Revision 01 November 2010.

Tokyo Sokki Kenkyujo Co. LTD. Precise & Flexible Strain Gauges, TML Pam E-101N, 2006.

Withers, P. J. and Bhadeshia, H. K. D. H. "Residual stress Part 1 – Measurement techniques", Materials Sci. and Tech., April 2001, Vol. 17 2001, pp. 355-355.

Withers, P. J. and Bhadeshia, H. K. D. H. "Residual stress Part 2 – Nature and origins – Overview", Materials Sci. and Tech., April 2001, Vol. 17 2001, pp. 366-375.