Post welding residual stress in P91 alloy steel

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Abstract: *The chromium-molybdenum steel pipe P91 is widely used in the power plants construction, because they can withstand higher temperatures and operating pressures, in order to increase operating efficiency and output. This material has a complex microstructure which is extremely vulnerable to convert into Austenite form near the temperature for heat treatment. During the welding procedure should be very carefully, because otherwise the residual stress installed post welding will reach high values. A series of experimental studies was carried out, which has shown the development in the magnitude of transverse and longitudinal residual stresses and the values in both directions were determined. For but welded joints the residual stresses in the three direction were measured and the results are reported here. For measuring was used the hole drilling method through "measuring balls" or electrical strain gauge. Except the experiments the finite element method was used to determinate the value and the distribution of the residual stresses. The experimental and FEM results were compared between them and no discrepancy was found.*

KEYWORDS*: RESIDUAL STRESS, TRANSVERSE STRESS, LONGITUDINAL STRESS, TRANSVERSE WITHDRAWAL, STRESS DISTRIBUTION.*

1. *Introduction*

The non-strictly metallurgical effects (deformations and tensions), produced by the execution of the welds, have been progressively analyzed and characterized since the 1940s, both on the basis of experimental tests and with the aid of mathematical models.

To date, it is important to know the mechanisms that govern their genesis in order to better manage manufacturing activities according to project expectations [1].

The properties of Grade 91 wholly depend on its chemical composition and microstructure. Welding P91 generally requires preheating the joint, maintaining interpass temperatures, hydrogen bakes, and postwelding heat treatment (PWHT).

The preheat temperature and interpass temperature was kept in the range of 200-250°C. The welding method used was GTAV with filler material ER90S-B9. In the figure 1, is shown the complete welding procedure.

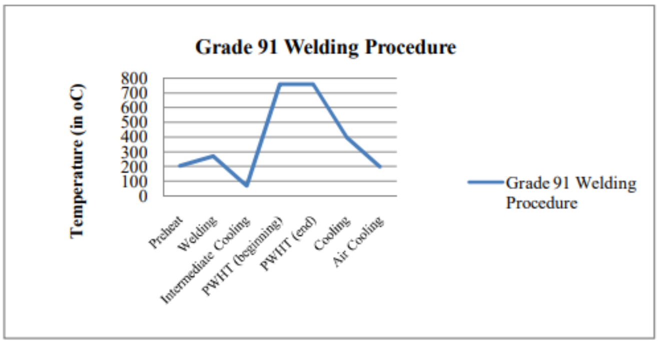


Figure 1. *Welding procedure of a seamless pipe p91.*

The figure 2 is shown the welding procedure for P91 pipe in site, during the preheating process.

Grade 91 Alloy Steel is a complex material to work upon. The most important and difficult task is to maintain its unique microstructure. Grade 91 is an upgrade to the regular Grade 22 alloy steel. In comparison with grade 22 alloy steel, following observations are made [2]:

- Reduction in wall thickness by two third; reduction in weight by 60%.
- Increase in allowable strength in 500 - 600°C range by 150%.
- Increase in oxidation limit by 40°C, enabling lower corrosion allowance.
- Increase in thermal fatigue life by a factor of 10-12.

Figure 2. *Preheating procedure of a seamless pipe p91.*

2. *Experimental results for transverse withdrawal*

The values that the transverse withdrawal can assume in the construction practice depend very much on the degree of constraint of the pieces, on the weight of the connected elements or they can also come from the use of assembly devices, specially designed to place the pieces in position and prevent deformations during and after welding. Establishing with precision the degree of constraint and then predicting the possible withdrawal on the basis of it, is often very difficult [3]. The values assumed by the withdrawal in the welded joints were determined by various experiments. For transverse withdrawal we will report some results taken from the experiments.

The diagram in figure 3, shows the variation of transverse withdrawal of butt-welded specimens with GTAV, as a function of the welding section and of the various thicknesses. It can be seen how the transverse withdrawal increases with the section of the weld, but much less rapidly, for greater thickness to be welded, it tends, however, to stabilize towards maximum values between 3 - 4 mm.

The diagram in figure 4, confirms the significant influence of the welding section, resulting from different shapes of the groove on the transverse withdrawal value. In the tests carried out with arc welding on a pipe with 14 mm of thickness, the X preparation determines a smaller withdrawal than the V one, and for each preparation the withdrawal is greater for more open angle of the bevel and for shorter distance between the edges.

Regarding the influence of executive factors on transversal withdrawal, it was found that this tends to increase with the number of passes [4]. In this regard, here below is shown the table 1, which includes the results of the experiments carried out. These results are for but welded specimens with thickness 14 mm, the V groove with angle of 90° and the distance between edges was 3 mm.

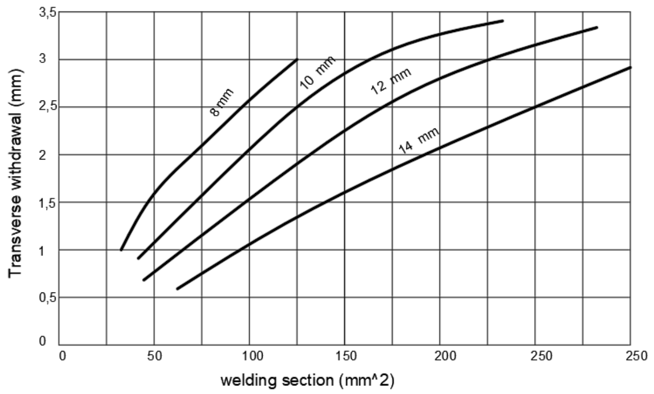


Figure 3. *Transverse withdrawal of butt-welded specimens, as a function of the welding section and of the thicknesses.*

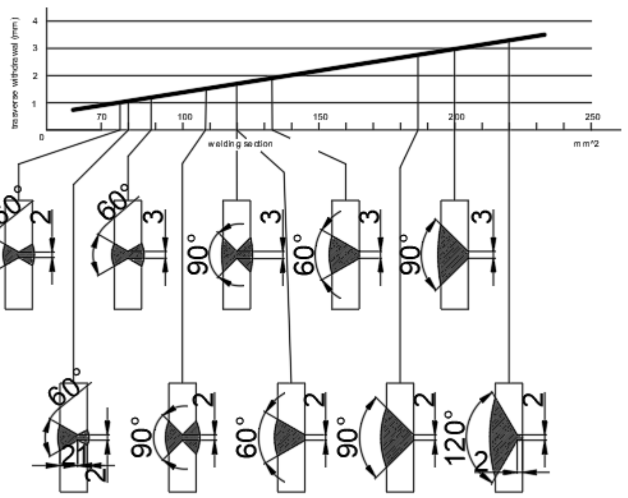


Figure 4. *Transverse withdrawal of butt-welded specimens, as a function of the welding section.*

Number of passes	Transverse withdrawal (mm)
6	3.15
8	3.45
10	4,10
12	4,35
15	4,55

Table 1. Transverse withdrawal of butt-welded specimens, as a function of the welding section.

The way each pass is performed also has some influence on the transversal withdrawal. In the case of arc welding, according to experiences made by Guyot, wide pass welding (with significant transversal movement of the electrode) produces a slightly greater transversal withdrawal than that with narrow passes side by side. Similarly, "step back" welding would produce a slightly less transversal withdrawal than continuous welding [5].

3. *Transverse and longitudinal stresses in butt weld joints*

The non-strictly metallurgical effects (deformations and tensions), produced by the execution of the welds, have been progressively analyzed and characterized since the 1940s, both on the basis of experimental tests and with the aid of mathematical models.

Bierett and Granning made a series of theoretical-experimental studies that showed the development in the magnitude of residual stresses in welding, both transverse and longitudinal in the butt welded joints and determined the values in both directions [6].

A lot of experiments were carried for different wall thickness. In the case of welding free samples without external constraints and therefore free to withdraw was found that for manual arc welding the distribution of stresses σ_L and σ_T is of the type indicated in the figures 5.

In a generic cross section x-x, figure 5, the trend of the longitudinal residual stresses indicated by the curve, shows that those stresses are in traction in the welded joint in the immediately adjacent area, and compression in the external areas.

The experiments have also shown that the distribution of longitudinal stresses is the same for all transversal sections, as indicated by the curve (blue color). From this it can be deduced that along a longitudinal plane y-y parallel to the axis of the joint and at a distance d from the axis itself, the σ_L remain constant and have a y value depending on the aforementioned distance d.

Figure 6 shows the distribution of transversal stresses (rotated 90° in their plane); from it, can be seen that these tensions, along the generic cross section, are always of the same direction (curves a and a '), and more precisely they are traction in the central part of the welded piece, while they become compression in the external areas.

This is shown more evident in the curve b, which represents the distribution of the σ_T along a generic longitudinal section y-y.

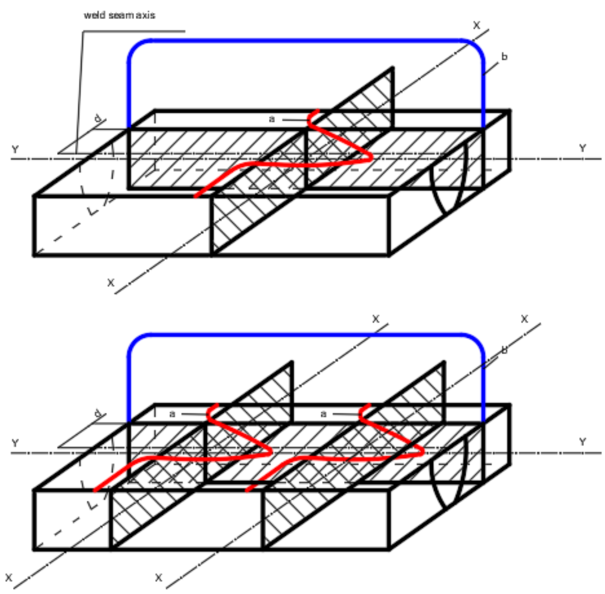


Figure 5. *The distribution of the longitudinal stresses in the butt welding joint.*

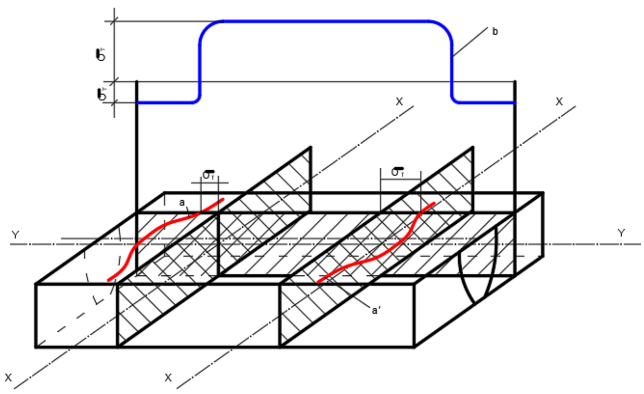


Figure 6. *The distribution of transverse stresses in the butt welding joint for.*

The distribution of residual stresses in a circumferential joint between pipes depends on the diameter and wall thickness of the pipe, the preparation and the welding sequence.

Strain gauge measurements were carried out on pipes with a diameter of 760 mm and a thickness of 11 mm, obtaining the transverse and longitudinal stress distribution as shown in Figure 7. The welding method used was GTAV with filler material ER90S-B9 [7].

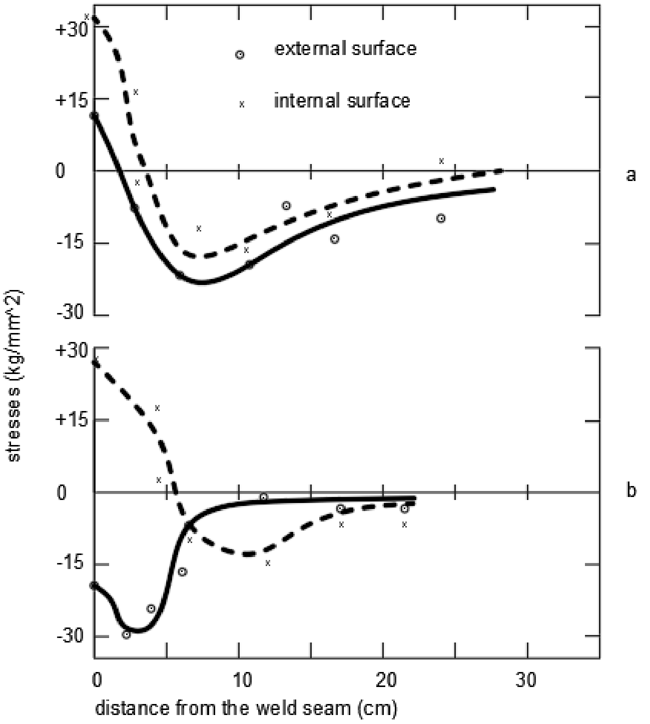


Figure 7. *Longitudinal and transverse residual stress distribution*

The trend of residual stresses was studied in the case of the pipes with a diameter of 250 mm and a thickness of 10 mm, with manual arc welding in the fixed position with horizontal axis. The results obtained are shown in the figure 8.

It appears clear that the higher states of stress, both for longitudinal residual stresses and for transverse stresses, occur on the internal surface and are in traction. An explanation of this could be given considering the different thermal gradients which during cooling affect the internal and external surfaces. Actually it has been experimentally verified that after the deposition of the last pass, during cooling, due to the greater heat exchange towards the outside, the internal wall was found in a temperature of about 80°C higher than the external wall, starting from temperatures (about 850C° - 900°C), below of which the differences in yield value are significant.

During the experiments were also analyzed the distribution of residual stresses along the thickness direction. In the case of welded pipes with a thickness greater than 10 mm, the residual stresses in the perpendicular direction can also become significant.

The figure 9 shows the distribution of residual stresses along the thickness direction in a butt joint, for chromium-molybdenum steel pipe P91, with X preparation, thickness 14 mm, diameter DN 1000 mm. The welding was executed with GTAV, alternately on both sides of the groove, in order to minimize distortion of the joint.

From the figure 9, it is noted that the longitudinal and transverse stresses are of traction in areas close to the sample surfaces. The transverse compression stresses, at the heart of the weld, are produced during the execution of the final filling passes of the groove.

In the figure 9.c is shown the distribution of the perpendicular residual stresses which vanishes at the two surfaces. Although this distribution is compressive in the case shown here, other researchers consider that there may be states of tensile stress even within the welded thickness, particularly for high thicknesses.

Moreover the experiments a study was carried out with finite element theory based on a joint model as shown in the figure 10. This model represent the joint between two pipes [8].

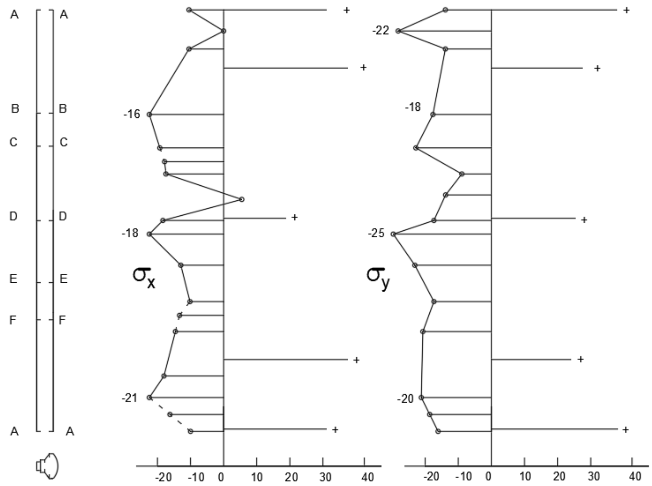


Figure 8. *The trend of residual stresses.*

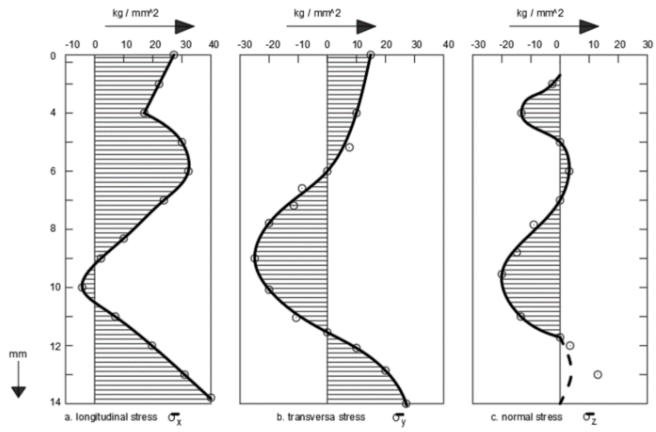


Figure 9. *The distribution of the residual stress along the thickness direction in the butt welding joint.*

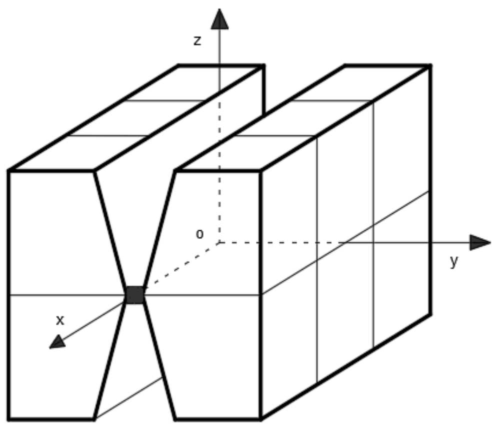
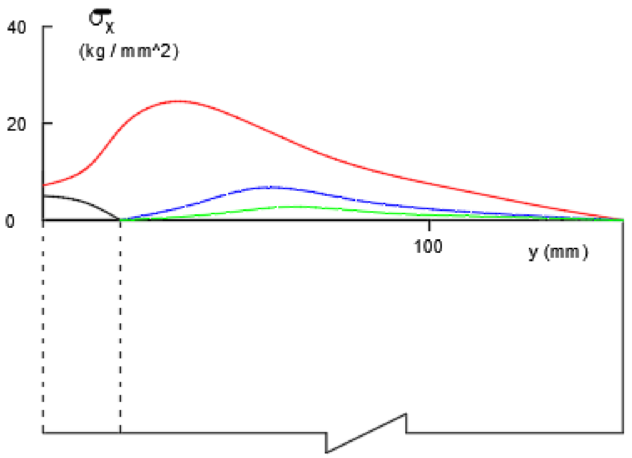


Figure 10. *The model used for the FEM study.*

The welding passes were deposited alternately on opposite sides of the groove in order to prevent angular distortion. It is a 9 Cr – 1 Mo steel and was welded with submerged arc procedure (50 kJ / cm) with similar filler material, and with a preheating of about 250°C.

In the figure 11a and 11b are shown the residual longitudinal stresses in correspondence to various filling levels of the groove (inter pass temperature 250°C) respectively on the surface of the sample (in the direction normal to the axis of the bead) and in the direction of the thickness. These distributions were obtained with three-dimensional elastic-plastic finite element analysis.



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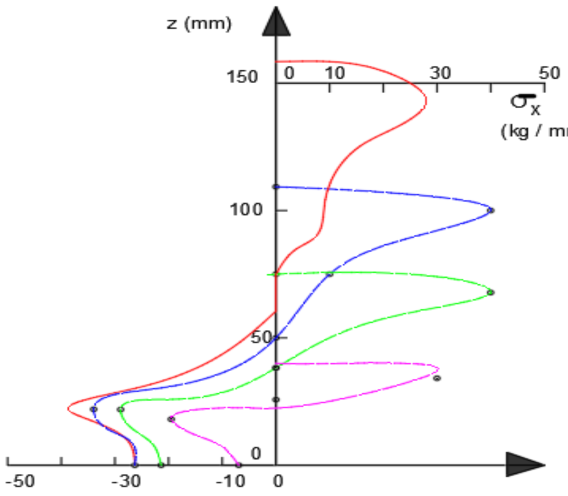

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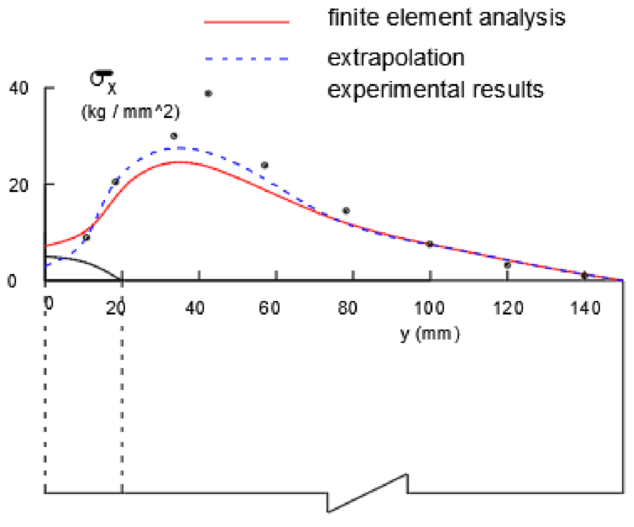
Figure 11a and 11b. *Trend of residual longitudinal stresses as a function of different filling levels.*

At the end of the welding, the distribution of the longitudinal residual stresses on the surface of the sample is shown in the figure 12a; it can be noted that the maximum value is displaced by about 20 mm with respect to the edge of the last pass. The figure 12b shows the distribution of the longitudinal residual stresses in the direction of the thickness at the axis of the bead and at two different distances from it. As shown in the figure 12, while at the external surface of the weld the residual longitudinal stresses are positive and of small entity, the highest value of these occurs at a certain depth, corresponding to some layers of passes.



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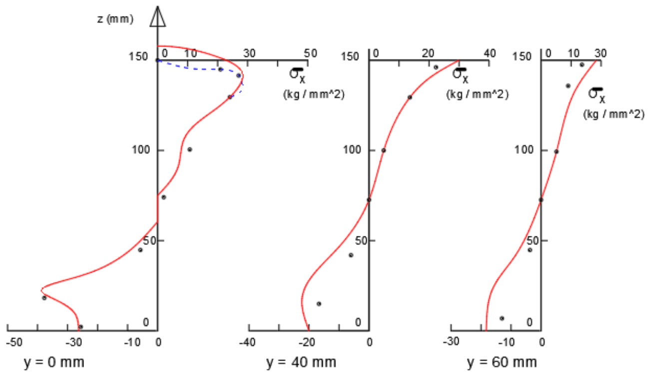

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Figure 12a and 12b. *Comparative distribution of stresses (experimental value vs values with FEM)*

4. *Method of measurement of residual stresses*

4.1 The hole drilling method (basic method)

This is a method for the measurement of tri-axial stress states, based on experiments conducted by Mathar. The principle involves the execution of the holes in the thickness and the measurement of deformations in the radial direction, as shown in the figure 13, through "measuring balls" or electrical strain gauges straddling the hole itself [9].

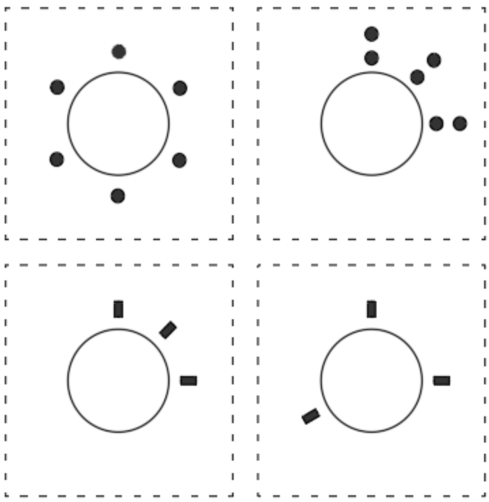

Figure 13. *Application of "measuring balls" or strain gauges to measure radial deformations.*

The method has been standardized by ASTM E 837-85.

Measured the deformations in the X and Y direction, it is possible to find the stresses σ_x and σ_y through the theory of elasticity applied to an infinitely thin plane, in which a circular hole is made, subject to a state of uniaxial tension. By substituting the data (diameter of the hole d_0 = 12 mm, measurement base d = 16 mm, ν = 0.3) the stresses can be expressed as a function of the deformations Δx and Δy:

$$\sigma_x = E\left[0.99*2\left(\frac{\Delta x}{d}\right) + 0.38*2\left(\frac{\Delta y}{d}\right)\right]$$

$$\sigma_y = E\left[0.99*2\left(\frac{\Delta y}{d}\right) + 0.38*2\left(\frac{\Delta x}{d}\right)\right]$$

In order to express the radial deformation ε_r as a function of the stresses σ_x and σ_y, it is possible to introduce the parameters A and B, functions of the elastic characteristics of the material and of the geometry of the measurement system.

$$\varepsilon_r = (A + B\cos 2\beta)\sigma_x + (A - B\cos 2\beta)\sigma_y$$

Where:

$$A = -\frac{(1-\upsilon)}{2E\left(\frac{d_0}{d}\right)^2}$$

$$B = -\frac{(1+\upsilon)}{2E\left[\frac{4}{(1+\upsilon)\left(\frac{d_0}{d}\right)^2 - 3\left(\frac{d_0}{d}\right)^4}\right]}$$

In the case of a state of biaxial residual stress of unknown direction, measurements made in at least three different directions are necessary (the relationships reported above do not take this general case into account). For this purpose, the method provides in its general version the use of strain gauge rosettes, as shown in figure 14, with the purpose of determining, in addition to the deformations, also the angle β between the direction of the main stress σ_1 and the direction of measurement σ_x.

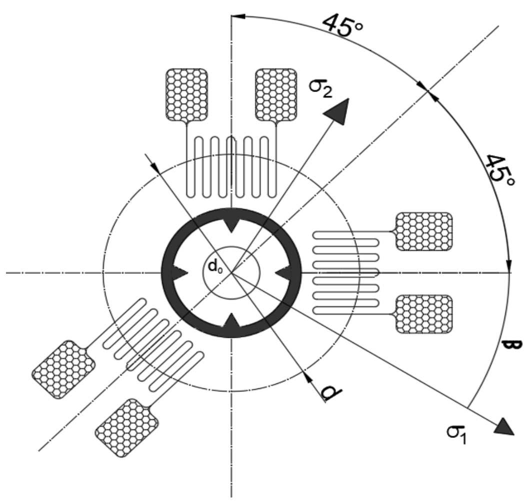

Figure 14. *Application of "measuring balls" or strain gauges to measure radial deformations.*

The angle β can be analytically expressed through the relationship:

$$\tan(2\beta) = \frac{(\varepsilon_{00} - 2\varepsilon_{45} + \varepsilon_{90})}{(\varepsilon_{00} - \varepsilon_{90})}$$

In general, the accuracy of the measurements depends, for this method, on the positioning of the measuring elements with respect to the hole. In the case of "measuring balls", they can be positioned at 1 mm from the edge, in that of strain gauges, at values between 2.5 and 3.4 of the d/d_0 ratio.

The diameter of the hole depends on the dimensions of the measuring elements (for example, the diameter d_0 equal to 1.5 - 3.0 mm and measurement bases equal to 1.5 mm are quite common).

It should be remembered that the method is based on models of elastic types, therefore the presence of stress states close to the yield point and/or the possibility of plastic-type deformations can false the results, providing absolutely unreliable results.

5. Results and discussion

In the distribution of transverse stresses it is noted that:

- Transverse stresses hardly exceed 100 N/mm^2 when welding with free withdrawal. With specimen embedded parallel to the welded joint, this value can be double.
- The maximum transverse stresses occur in a strip straddling the joint axis. They are positive (tension) in the central area and negative (compression) at a certain distance from the axis.
- The larger heating produces maximum values of transversal tension, a little less than those generated by a more restricted heating, in the case of free specimens. In the case of embedded test pieces, the opposite occurs, i.e. manual arc welding tends to cause transverse stresses lower than those of other mechanized processes. This is in harmony with the fact that the transverse withdrawal tends to increase with the width of the heated area, and therefore it is logical that the stress which represents the equivalent of the prevented deformation also tends to increase with it.
- The remote parts of the joint are generally compressed transversely. This distribution of transversal stresses is an advantage, because it can make the extremity defects (craters, disparity of shape, incompleteness, etc.) less dangerous. These kind of defects are much more frequent in the extremity than in the central areas.

In the distribution of the longitudinal stresses it is noted that:

- Longitudinal stresses, given that welding always takes place in conditions of strong self-constraint, tend to very high values and they easily can reach the elastic limit of the material and can consequently cause plastic deformations of the welded area.
- Manual arc welding produces maximum stresses higher than those caused by processes characterized by greater heat input. Often in both cases, but more frequently in the case of the manual arc, the elastic limit is exceeded.
- The welding area is tensed, while the lateral ones are compressed for the internal surface and it is all in compression for external surface of the pipe.
- The constraints which block the pieces parallel to the axis of the welding have no practical influence on the trend and on the value of the longitudinal tensions.

6. Conclusion

Grade 91 Alloy Steel is a complex material to be welded. The most important and difficult task is to maintain its unique microstructure. If the welding procedure is not done as per the specified guidelines given in the codes, the material properties can be ruined permanently. The conditions of failure and the methods to prevent them must be followed in order to ensure safe and successful hot working on the material without disturbing its microstructure. If the PWHT is carefully performed the material is relaxed and the residual stress are not relevant.

7. References

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