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Investigation of residual stress development in spiral welded pipe

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ABSTRACT

The residual stresses in spiral welded pipe (SWP) are generated due to localized plastic deformation in the weld-metal and the heat affected zone (HAZ), which cause detrimental effects on the reliability of the pipes. Therefore, it is necessary to investigate these stresses to ensure safe service and operation of pipes used in oil and gas industry. The most commonly used techniques for the evaluation of residual stresses in industries are the split ring test and the hole drilling method. In the experimental part of this work, the semi-destructive hole drilling experimental technique has been adopted for analyzing the stresses in the pipe. The distribution of residual stresses is calculated through different mathematical procedures, such as uniform method, power series method and integral method. The second part of this work consists of finite element (FE) modeling of the split ring test. It is done by sequentially coupling the thermal and structural analysis of welding to assess the adequacy of the split ring method for the estimation of weld residual stresses. Furthermore, the numerically predicted residual distributions during welding are compared with experimentally calculated values using hole drilling method and it is found in good agreement.

1. Introduction

Spiral welded pipes are mostly used in industrial sectors for transferring and conveying fluids from one location to another. Steel pipe is welded from both inside and outside with spiral seam along the entire length of the pipe. The demand of these pipes has been continuously increasing on which non-destructive as well as destructive testing are performed for the assurance of the product quality.

Welding generates residual stress of remarkable level. The significant influences of such stresses can be distortion and deformation, metal shrinkage, dimensional instability, change in microstructure, brittle fracture and cold cracking. The fatigue life of the product is directly affected because of such residual stresses. The research studies have been carried out to understand the interaction of welding and its subsequent effects during the manufacturing of spiral welded pipes for the improvement of their qualities. Knoop (2003) in his report discussed the modern technology of two-step process in the manufacturing of spiral. He explained its qualitative and economical advantage over the conventional procedure. Arif et al. (2011) analyzed the spiral laser welding of a mild steel tube. They modeled moving volumetric heat distribution as a laser heat source. The effects of different welding speeds were also studied. The residual stresses were measured by XRD technique and metallurgical examination was done by optical microscope and SEM. In their study, it was found that high value of von Mises stress occurred in weld region after cooling and hardness in weld region was higher as compared to the base metal. Forouzan et al. (2012) studied the submerged arc welding of spiral welded pipes. The Goldak heat source distribution was applied by using un-furl mapping technique in which pipe was considered as a flat plate. The computational cost was reduced by using solid and shell element and the transition between them were defined by multi-point constraint technique. The hole drilling measurement was performed for validation purpose. The hydrostatic test was also simulated through ramp loading of internal pressure and it was concluded that the test causes the reduction of high tensile stresses. Dong et al. (2006) used three dimensional shell model for predicting the residual stresses in a long spiral pipe. Forming induced residual stresses, plate forming and radial expansion were determined by using plane strain model. Furthermore, their interaction with welding was studied. In addition, cold expansion and its effects were studied. It was found that the cold expansion had a beneficial effect on the hoop residual stress while detrimental effects was observed on residual longitudinal stress in weld component.

Different methods, procedures and techniques have been adopted for the assessment of residual stresses in the component.

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Each of the method has its certain limitation, capability, advantage and accuracy depending upon the nature of stress. The methods for residual stress measurement are based on the destructive, non-destructive and semi-destructive techniques. Hole- drilling is an advent technique for measuring the residual stress. It is relatively simple and quick. Due to insertion of very small hole in component, it is characterized as a semi-destructive technique. The continuous research is growing to implement this method for identifying the new measures for calculating the residual stress such as spline, integral and power series method (Petrucci and Zuccarello, 1998). The investigations are being carried out to make this method more accurate and reliable with less uncertainty errors. The drilled hole is assumed to be absolute center of the strain gage rosette. Wang (1979) studied the misalignment errors associated with eccentric hole during the experimentation. The error analysis was performed and it was found that 10% off-center would cause the variation of stress by five percent. Ajovalasit (1979) obtained formulae to calculate the actual residual stress by incorporating the eccentric parameters of the hole due to the misalignment. The application of this method is widely reported to estimate the residual stress field and validation of finite element model. Akbari and Sattari-Far (2009) experimentally measured the surface residual stress for dissimilar weld pipes and the effect of magnitude of heat input on the stress distribution is studied. Deng et al. (2008) analyzed the multi-pass welding in the austenitic stainless steel. The hoop and axial stresses are measured using electric resistance strain gage mounted on both inner and outer side of the pipe to verify the 2D axisymmetric model. The similar strategy is adopted for the authenticity of stress distribution in three dimensional circumferentially arc welded pipe (Malik et al., 2008). The regression based model was developed in (Olabi et al., 2007), for minimization of the residual stress in the heat affected zones of AISI 304 plate in which principal stress magnitude and directions were calculated in HAZ using hole drilling method. The residual stresses, before and after the hydrostatic test, in spirally welded pipe were predicted by Forouzan et al. (2012) using numerical technique. The justification and validation of results are made through experiments using this technique.

The split ring test method is another method which relates the stress field to the amplitude of opening or closing of the ring (Kyriakides and Corona, 2007). In ASTM standard practice E1928 (ASTM International, 1999), similar approach based on split ring test is used for calculating the circumferential residual stresses in thin walled tubing. These formulas were based on Sachs and Espey method which were related to the change in diameter upon splitting. The same procedure was depicted for the quenched tube (Totten et al., 1993). Dong et al. (2006) presented the three dimensional welding simulation and also performed splitting on a welded pipe ring. It was found that different hoop deformation could occur depending upon the location of cut, near or away from the weld seam.

The current work is divided into two parts. The first part deals with the residual stress measurement of spiral welded API 5L X70 high grade steel pipe experimentally through hole-drilling method. Different stress calculation procedures were adopted and compared. The second part is the finite element simulation of the welding process of spiral welded pipe. Thermal calculations were sequentially coupled with structural analysis to provide the residual stresses. Gaussian heat distribution was considered for the modeling of moving heat source which is generated through arc in welding. The FE Model was validated by the results of experimental study performed in the first part of this work. Finally, split ring test was numerically simulated using FE model and the results were compared to the formulas of bending residual hoop stress given in the literature.

2. Experimental methods

2.1. Hole drilling strain gage method

The principle of hole drilling method is based on disturbance in stress equilibrium due to relieved stresses in the locality of hole region causes the local strains to correspondingly change. An experimental setup is established in the KFUPM Mechanical Stress Lab, for the residual stress measurement in spirally welded API 5L X70 high grade steel pipe ring. Initially strain gages are mounted on the inner side and, then by turn, are placed on the outer side of the ring. The five strain gage rosettes of type CEA-XX-062UM-120 were positioned, in line such as these are perpendicular to the weld seam. The specification of the gage can be seen in Table 1. One of the strain gages was on the weld center line while the other two were attached on the both side of the seam. The equal distance of 2.5 cm was maintained between the rosettes. The pictorial view of the mounted gages on inner and outer side can be seen in Fig. 1.

First, following the instruction in bulletin B-129-8 of micro-measurement system (Vishay Micro-Measurement Group, 2010a,b,c, 2011a,b,c), a clean and uncontaminated surface was prepared. Then, the strain gage rosette was installed firmly according to bulletin B-127-4 with M-bond 200 adhesive. The application notes TT-603, TT-606 and TT-609 were followed for the connection of strain gage with the bondable terminals and further with lead wires. The whole assembly was aligned according to the RS-200 milling guide instruction manual. The most important and crucial step was aligning the cross hairs which were seen through microscope and adjusted with rosette cross hairs. It must be assured that exact center has been achieved. The P3 strain indicator was connected for data acquisition and recording. The initial zero strain was balanced on the indicator for each rosette. The relaxed strain measurements were obtained during drilling and then principal stresses from the measured strains were determined using data reduction relationships.

There are different methods developed for residual stress calculation such as uniform, power and integral methods. The nature and distribution of residual stress to be measured are not known in advance. *Uniform method* is based on linear elasticity theory and relates the relieved component of strains with the maximum and minimum principle residual stress and their angle β using following expressions.

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

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

$$\beta = \frac{1}{2}\tan^{-1}\left(\frac{\varepsilon_1-2\varepsilon_2+\varepsilon_3}{\varepsilon_1-\varepsilon_3}\right) \tag{3}$$

where

$$\bar{A} = -\frac{1+\nu}{2E}\bar{a} \quad \bar{B} = -\frac{1}{2E}\bar{b}$$

where the $\sigma_{\max}$ and $\sigma_{\min}$ are the maximum and minimum principal stress with β angle of orientation, ε_1, ε_2 and ε_3 are measured relieved strains, E is the modulus of elasticity, ν is the Poisson ratio, $\bar{A}$, $\bar{B}$, $\bar{a}$ and $\bar{b}$ are the calibration coefficients.

Power series method and *integral method* are mathematical procedures which have been developed for calculating non-uniform residual stress by incorporating the influence functions in order to construct the experimental measurements. The strain response using power series variation with depth was firstly introduced by Schajer (1981). In this method, the unknown residual stress field is approximated by the terms of the power series (Eq. (4)). The series coefficients were estimated through finite element calculation by