Measurement 106 (2017) 152–160

Contents lists available at ScienceDirect

Measurement

journal homepage: www.elsevier.com/locate/measurement

On the measurement of sub-surface residual stresses in SS 304L welds by dry ring core technique

A. Giri [a], M.M. Mahapatra [b,*]

[a] Department of Mechanical and Industrial Engineering, Indian Institute of Technology, Roorkee, Uttrakhand 247667, India
[b] School of Mechanical Sciences, Indian Institute of Technology Bhubaneswar, Jatni, Khurda, Odisha 752050, India

ARTICLE INFO

Article history:
Received 18 February 2016
Received in revised form 23 March 2017
Accepted 28 April 2017
Available online 2 May 2017

Keywords:
Residual stress
Dry ring core
Regression analysis
FE analysis
Weld joint

ABSTRACT

Sub surface residual stresses in thick multi-pass stainless steel butt welded joints were measured by dry ring core technique. To accomplish the task of dry ring coring, special tools were developed such that machining induced stresses were negligible. Established equations, analytical methods and regression correlations were used in the measurement. A database of mathematical relations of residual stress values was also developed using the response surface methodology. A 3-D finite element (FE) model was used to prepare the residual stress field data at the different stress ratios at various depths of the welded joints. Further, this data was used to develop the regression equations as well as to determine the calibration coefficients.

1. Introduction

Manufacturing processes like welding, rolling, casting and machining introduce the residual stresses in the engineering component. The nature and magnitude of residual stresses depend upon the various factors like processes, process parameters, constraints and material properties. Techniques like Sectioning method, Blind hole drilling, Ring core method, X ray, Neutron diffraction are used for the determination of locked-in residual stresses and their orientations [1,2] in engineering components. However, for the measurement of macro residual stresses, stress relaxation techniques using mechanical and electrical sensors are preferred. Such techniques have been proved to be more accurate in measuring locked in residual stress compared to nondestructive methods such as by X-ray diffraction method. Blind hole drilling technique is one of the widely used stress relaxation technique [3,4]. However, the blind hole drilling method is generally used for measuring residual stresses up to 1.5 mm depth. Moreover, calculation of residual stresses using blind hole drilling method is associated with possibility of error that arises due to yielding of the blind hole outer surface and stress concentration effect of multi-point cutting tool [5]. Error estimation of such technique is a major concern in accurate estimation of residual stress.

Ring core method is a semi destructive method used for the measurement of uniform and non-uniform locked-in sub-surface residual stresses in the materials. Unlike the blind hole drilling process, in ring core method, an annular ring is cut concentrically around the strain gauge rosette in the successive depth of cut, resulting the separation of core from the material. Thus the residual stresses presented in the core are released due to the material removal around it, resulting the deformation of core. This deformation is measured in the terms of relieved strains by the strains gauge rosetteat the core. Although this process produces much more damages to the specimen than blind hole drilling process, the residual stresses can be measured at greater depth, generally up to 5–7 mm. This method is also less susceptible to error due the material cutting which is more severe in hole drilling method [6].

Civin and Vlk [7–9] studied the effect of various factors during ring core method like model width, length, thickness and cutting tool radius on relaxed strains corresponding to applied pressure in simulation by FEM. Authors also determined the calibration coefficients used in the analytical evaluation of residual stress by ring core method in both uniaxial and biaxial state of stress [8]. Researchers also worked on the determination of principal residual stress and their orientations by incremental strain method [9]. Vaclavik et al. [10] studied the residual stress measurement by ring core method. They determined the calibration coefficients using the full scale model (having the core, inner radius 7 mm and outer radius 9 mm in the middle of outer surface of model) by FEM sim-

* Corresponding author.
E-mail addresses: manasfme@iitr.ernet.in, manasfme@gmail.com (M.M. Mahapatra).

http://dx.doi.org/10.1016/j.measurement.2017.04.043
0263-2241/

Nomenclature

K_1 & K_2	calibration coefficients
σ_y	yield strength
σ_X & σ_Y	stresses in X & Y directions respectively
σ_L & σ_T	longitudinal & transverse residual stresses
ε	strain
z	depth
$d\varepsilon/dz$	strain derivative
d_i	Trepan tool internal diameter
d_o	Trepan tool outer diameter
E	Young modulus
ν	Poisson ratio
ISM	incremental strain method
OD/ID	outer diameter/inner diameter

ulation. Results obtained by the ring core analysis were also compared with hole drilling method [10]. Hu et al. [11] proposed the ring core method with 3D digital image correlation technique for the measurement of residual stress. This method was validated with conducting the uniaxial compression test [11]. Nau and Scholtes [12] developed the application tool for evaluation of residual stress by ring core or hole drilling method using the finite element (FE) modeling. Recently, the ring core method was explored by Menda et al. [13–16]. The authors worked on different simulation approaches by analyzing the ring core models using commercial finite element codes. Calibration coefficients were determined for simulation approaches by using the integral and differential method and respective errors were compared in their work [13]. Authors also studied the effect of milling cutter geometry by providing the slope at the bottom of teeth of mill cutter [14]. Similarly the influence of specimen model geometry was investigated by the authors as reported in the literature [15]. Barsanti et al. [17] proposed integral method for ring core technique by using the harmonic axi-symmetric FE model. Yazdi et al. [18] studied the residual stresses in quenched parts to assess the quenching for fatigue life calculation. It was found out that the residual stresses due to quenching were compressive at the surface while tensile at the middle of part [18]. Beghini et al. [19,20] proposed the incremental strain distribution methodology to determine the residual stress distribution. Authors also studied the residual stresses in cladded plates by the incremental strain distribution method [20].

Ring core method is advocated for sub-surface residual stress measurement. However, electric discharge machining (EDM) based trepanning operation for ring coring is cumbersome and time consuming. Investigators have therefore opted for dry ring core method to avoid trepanning operation by EDM. While doing dry ring core method, care has to be taken to avoid possible machining stress that may be induced in the workpiece which leads to inaccuracy in measurement. From the literature review, it is noted that authors worked on the feasibility of dry ring core technique such as determining the calibration coefficients, determination of principle stresses, measurement of stresses in the shaft component etc. However, work involving application of dry ring core method for determining sub-surface residual stresses in multi-pass thick SS 304L butt welded joints is rarely found in literature. In certain critical applications, stress relieving operations of SS 304L welded joints are not recommended as it may lead to precipitation of chromium carbide at the grain boundaries resulting the formation of chromium depleted zones which deteriorates the weld properties. Further, it is undesirable to have high residual stresses in stainless steel welded joints. So it becomes necessary to determine the residual stresses. The aim of the research work was to measure sub-surface residual stress in thick SS 304L butt welded joints. Through FE modeling, a data base was also created for a range of biaxial applied stresses. This data base was used for the determining the calibration coefficients for analytical solution and to provide the direct solution in the form of mathematical relations to determine the residual stresses.

2. Formulations of ring core method

Incremental strain method (ISM) is common practice followed to analytically evaluate the residual stresses by ring core method. ISM is based on the incremental difference between the relieved strains $d\varepsilon$ measured at the top of core after a particular depth increment dz. Incremental strains $d\varepsilon$ measured by the stains rosette for a particular depth increment dz, are not influenced by the previous depth steps and stresses in the perpendicular directions of the measuring grid [9,13]. In ISM, calibration coefficients K_1 and K_2 are to be determined with respect to depth of cut for a particular type of milling cutter geometry. Eqs. 1–3 show the stresses in the directions a, b and c of three elements stains rosette [9,10]. Fig. 1 shows the schematic of orientations of measuring grids a, b and c in strain rosette.

$$\sigma_a = \frac{E}{K_1^2 - \mu^2 \cdot K_2^2} \cdot \left(K_1 . \frac{d\varepsilon_a}{dz} + \mu \cdot K_2 . \frac{d\varepsilon_c}{dz} \right) \tag{1}$$

$$\sigma_b = \frac{E}{K_1^2 - \mu^2 \cdot K_2^2} \cdot \left[K_1 . \frac{d\varepsilon_a}{dz} + \mu \cdot K_2 . \left(\frac{d\varepsilon_a}{dz} - \frac{d\varepsilon_b}{dz} + \frac{d\varepsilon_c}{dz} \right) \right] \tag{2}$$

$$\sigma_c = \frac{E}{K_1^2 - \mu^2 \cdot K_2^2} \cdot \left(K_1 . \frac{d\varepsilon_c}{dz} + \mu \cdot K_2 . \frac{d\varepsilon_a}{dz} \right) \tag{3}$$

where $\frac{d\varepsilon_a}{dz}, \frac{d\varepsilon_b}{dz}$ & $\frac{d\varepsilon_c}{dz}$ are the strains derivatives measured in respective directions of strain rosette.For the biaxial analysis, calibration coefficients K_1 and K_2 can be described by Eq. (4–6).

$$K_1 = \frac{E}{\sigma_1 (1 - k^2)} \cdot \left(\frac{d\varepsilon_1}{dz} - k . \frac{d\varepsilon_2}{dz} \right) \tag{4}$$

$$K_2 = \frac{E}{\mu . \sigma_1 (1 - k^2)} \cdot \left(k . \frac{d\varepsilon_1}{dz} - \frac{d\varepsilon_2}{dz} \right) \tag{5}$$

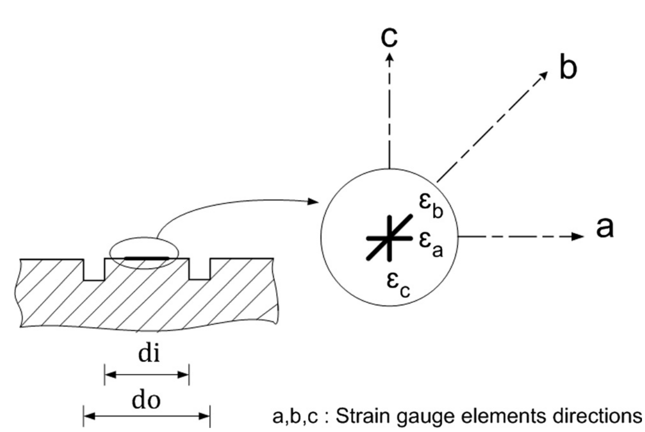

Fig. 1. Schematic of ring core technique with three elements strain rosette.