

Map of Residual Strain in a Welded Aisi 304 Steel Component, Obtained by Neutron Diffraction

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Abstract

Neutron diffraction has been used to determine the residual strain in an internal section of a butt welded AISI 304 pipe. In particular the iso-strain map of the 111 planes having a fixed direction was obtained. At our knowledge, this is the first weld studied by using the "neutron scanner" method (ref. 10).

Riassunto

Mediante l'uso della diffrazione neutronica si è determinata la deformazione residua in una sezione interna di tubo d'acciaio AISI 304 saldato testa a testa.

In particolare si è ottenuta una mappa dei livelli di isodeformazione relativa ai piani 111 con un fissato orientamento. A nostra conoscenza questa è la prima saldatura studiata con il metodo dello "scanner a neutroni" (ref. 10).

Introduction

Residual stress due to welding processes in heavy steel sections can reach high values, affecting the strength of welded joints. Its evaluation is therefore of fundamental importance for the assessment of the welding process, particularly for materials like stainless steel, where the welding process can induce tensile residual stresses. Most of the available non-destructive methods provide only surface or near-surface residual stress, whereas the through-thickness stress distribution is essential for full evaluation of the weld characteristics. From this point of view, the neutron diffraction technique provides a powerful tool for accurate and non-destructive measurements of the internal strain field.

It has been already proved that strain analysis by means of neutron diffraction is feasible with the available neutron sources and can be helpful in solving residual strain problems of practical interest [1-12]. As in the well known X-ray diffraction technique, neutron diffraction strain analysis is based on the precise determination of the interplanar spacing d of one particular set of diffracting planes. The great advantage of neutrons is that they can penetrate deeply in many materials; so that strain distributions can be measured through the bulk and not only in the near-surface region. Different methods can be used for accurate evaluation of the strain field by means of neutron diffraction technique, in two and three dimensions [9].

A particularly interesting method for the welding control is considered in the following. It consists of obtaining a map of the iso-strains through a given plane inside a sample. It requires a two dimensional movement of the tested component and only one direction of strain is considered [10].

Experimental section

Sample preparation

The analysed sample was cut out from a 28" piping mock-up, assembled with two portions of AISI 304 pipe butt welded (Fig. 1). The dimensions are 135 mm high, 175 mm long and 35 mm thick, where 135 mm and 35 mm are the sizes of the welding cross section.

The chemical composition of the steel, reported in Table 1, confirms the low carbon content that assures a good corrosion resistance in welded structures. The welding sequence was (Fig. 1): consumable

insert fusion in the first step; then two TIG passes; lastly twenty-six SMA passes distributed on ten layers to complete the fillet weld.

TABLE 1 - Chemical composition of AISI 304 stainless steel

Element	wt%
Cr	18.12
Ni	15.56
Mn	1.37
C	0.069
Mo	0.37
S	0.014
P	0.027
Si	0.34
Fe	bal

Neutron diffraction measurements and results

Neutron diffraction strain analysis is based on the determination of the lattice strain by precise measurements of the interplanar distance, by using the Bragg law:

$$2 d \sin \theta = n \lambda \quad (1)$$

where d is the crystalline lattice spacing corresponding to a Bragg reflection, 2θ is the scattering angle, λ is the neutron wavelength and n is the order of the reflection, which will be equal to one in the following. The lattice strain ε is calculated by the equation:

$$\varepsilon = (d - d_0)/d_0 \quad (2)$$

where d and d_0 are the lattice spacing of the strained and unstrained material respectively. The direction of the measured strain in the sample is that of the scattering vector $\underline{Q} = \underline{K} - \underline{K}_0$, being $\underline{K}$ and $\underline{K}_0$ the scattered and the incident neutron wave vectors, of magnitude $2\pi/\lambda$ [5]. The investigated region of the sample is defined by the interesection of the incident and diffracted beams. In order to explore different zones, the specimen is translated step-wise with respect to x and y axes, integral with the slits positions. The principle of the neutron strain scanner is illustrated in Fig. 2.

The neutron diffraction experiments were carried out at the Laboratoire Léon Brillouin by using the two axis spectrometer G4.2, situated on a cold guide of the reactor Orphée. A $\Delta d/d$ sensitivity of about 0.02% can be achieved at $2\theta = 90^\circ$ by using a pyrolytic graphite monochromator and a collimation of 0.25° . Measurements have been performed by keeping the neutron wavelength fixed at $\lambda = .33$ nm and varying the scattering angle. The stronger reflection (111) was considered in order to evaluate the lattice parameter. The Bragg diffraction peaks consisted of about 30 experimental points, spaced 0.1° each other. Different measurement times, from half an hour to 24 hours, were used at the different explored points, in order to have statistical errors of the same order of magnitude. The peak center position was calculated by fitting the experimental data with a Gaussian function.

The geometry of the experiment is shown in Fig. 3; the gauge volume was $2.5 \times 2.5 \times 20$ mm³. The direction of the measured deformations is perpendicular to the surface of the sample and parallel to the x axis.

The weld was considered as symmetrical with respect to the xz plane, thus only one half of the component was investigated. The measurements were performed at constant z ($z = 85$ mm), corresponding to a central part of the sample, in order to avoid boundary effects.

A preliminary test was performed on the sample in order to determine the highest reachable depth inside the component. To this end, the diffracted intensity of the (111) reflection was reported as a function of the investigated volume position (Fig. 4), and it was found that the thickness of the investigated region cannot exceed 15 mm. In fact, as the tested region is moved progressively inside the weld, the neutron diffracted intensity rapidly decreases as reported in Fig. 4 and at $x = 15$ mm it reaches too low values for sufficiently precise determination in a reasonable long time. The limit position for which the sampling volume is all inside the component can be assumed to correspond to the maximum of diffracted intensity, i.e. centered at about 2 mm from the external surface.

Because of the high thickness of the welding cross section (35 mm), the measurements were restricted to the first 14 mm from the surface, on both sides of the sample. Therefore 7 mm, corresponding to the central part of the welding cross section, remained unexplored.

Measurements were performed by centering the sampling volume at different points spaced by 2 mm along the lines (a-g) reported in the insert of Fig. 5, i.e. along the x direction and at distances y (mm) = 30 (line a), 20 (line b), 15 (line c), 10 (line d), 5 (line e), 2.5 (line f) and 0 (line g) from the weld center. The values obtained for the (111) interplanar distance along these lines are reported in Fig. 5 as functions of the depth. In Fig. 6 d_{111} values are reported as functions of the distance from the weld center, for fixed depths.

In order to derive strains from the measured interplanar distances, the reference spacing d_0 had to be obtained. The determination of d_0 is in general a problem, as it can be difficult to find a truly unstrained material, and several methods have been proposed [11]. In the present investigation the d_0 value has been evaluated by measuring it in a powder obtained by grinding a small piece of the specimen:

$$d_0 = (0.20685 \pm 1.7 \times 10^{-5}) \text{ nm}$$

The strains through the considered plane $z = 85$ mm were then calculated by using equation (2). This choice can affect the absolute value of the strain inside the weld (in fact a different d_0 can occur) but we assume that it does not affect the strain gradient both inside and outside the welded region. The isostrain map in that plane have been then obtained by using a computing code based on the Kringing method [13] for creating a regularly spaced grid from the experimental data. The results are shown in Fig. 7.

Conclusions

In a welded component made of AISI 304 steel the strain map was obtained in a plane across the weld. Higher strain gradient were found in the welded region, but changes of the d_{111} interplanar distance with respect to the measured unstrained value were also obtained in the surrounding regions.

The usefulness of neutrons in the determination of residual strain in structural components has been more and more considered in the last years [1-12]. In particular two useful features of the neutrons as a tool for materials sciences and engineering should be emphasized: firstly, with respect to other investigation techniques they can give full information, in a non destructive way, also about the through-thickness stress distribution. Moreover they give information on the actual state of a component: this fact was pointed out in a recent work in which a comparison has been performed between the strains in a thermally fatigued component as obtained by neutron diffraction and those forecast by the Finite Elements Analysis [12]. The agreement between the results of the two techniques was good and the differences were attributed also to the strain induced by preparation and handling of the sample, which could not be considered in the theoretical calculations.

In order to compare the strain obtained by using the neutron diffraction with the results from other techniques, one must consider that the elastic component ε of the residual strain is evaluated in the neutron measurements. Its relation with the stress tensor σ is given by:

$$E \varepsilon = (1 + \nu) (\alpha_1^2 \sigma_{xx} + \alpha_2^2 \sigma_{yy} + \alpha_3^2 \sigma_{zz} + 2\alpha_1 \alpha_2 \sigma_{xy} + 2\alpha_1 \alpha_3 \sigma_{xz} + 2\alpha_2 \alpha_3 \sigma_{yz}) - \nu(\sigma_{xx} + \sigma_{yy} + \sigma_{zz})$$

ν being the Poisson's ratio, E the elastic modulus and α_1 , α_2 and α_3 the strain direction cosines in the laboratory frame of reference. The elastic modulus E in the considered case of neutron diffraction is not the bulk elastic modulus but depends on the particular plane considered and in the case of stainless steels it can vary by a factor up to about two.

At our knowledge, this is the first application of the "neutron scanner", reported in ref. 10, to obtain a two - dimensional map of strain in a welded material.

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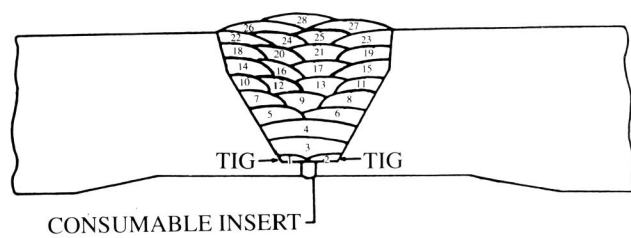


Fig. 1:
Preparation of the TIG weld and weld pass sequence.

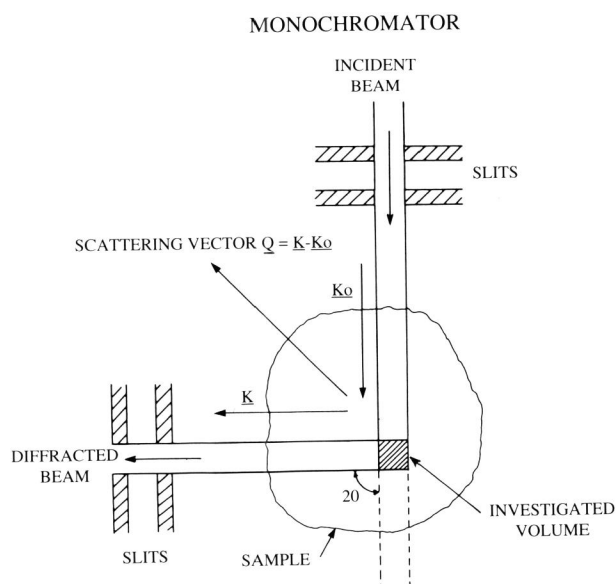


Fig. 2:
Schematic illustration of the neutron strain scanner.

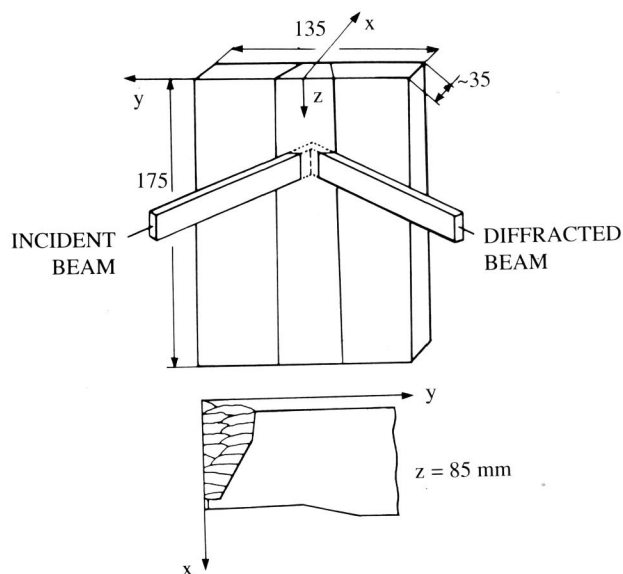


Fig. 3:
Geometry of the experiment on the weld component (Sizes are in mm).

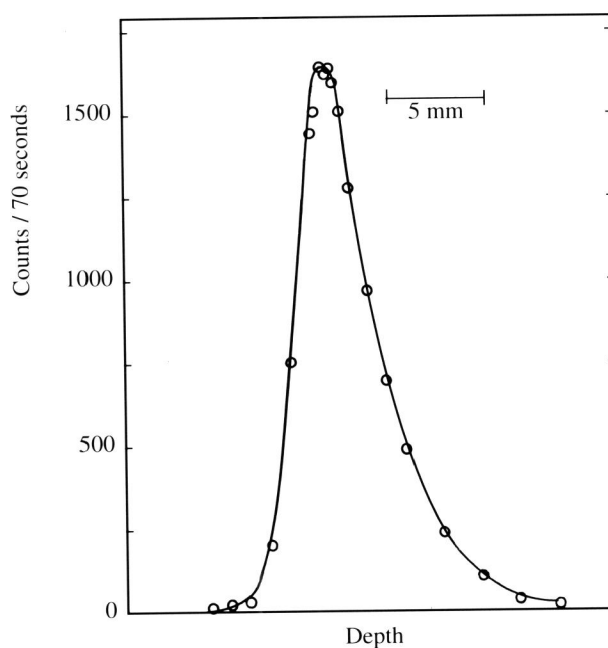


Fig. 4:
Peak intensity of the (111) reflection vs. depth along the x direction.

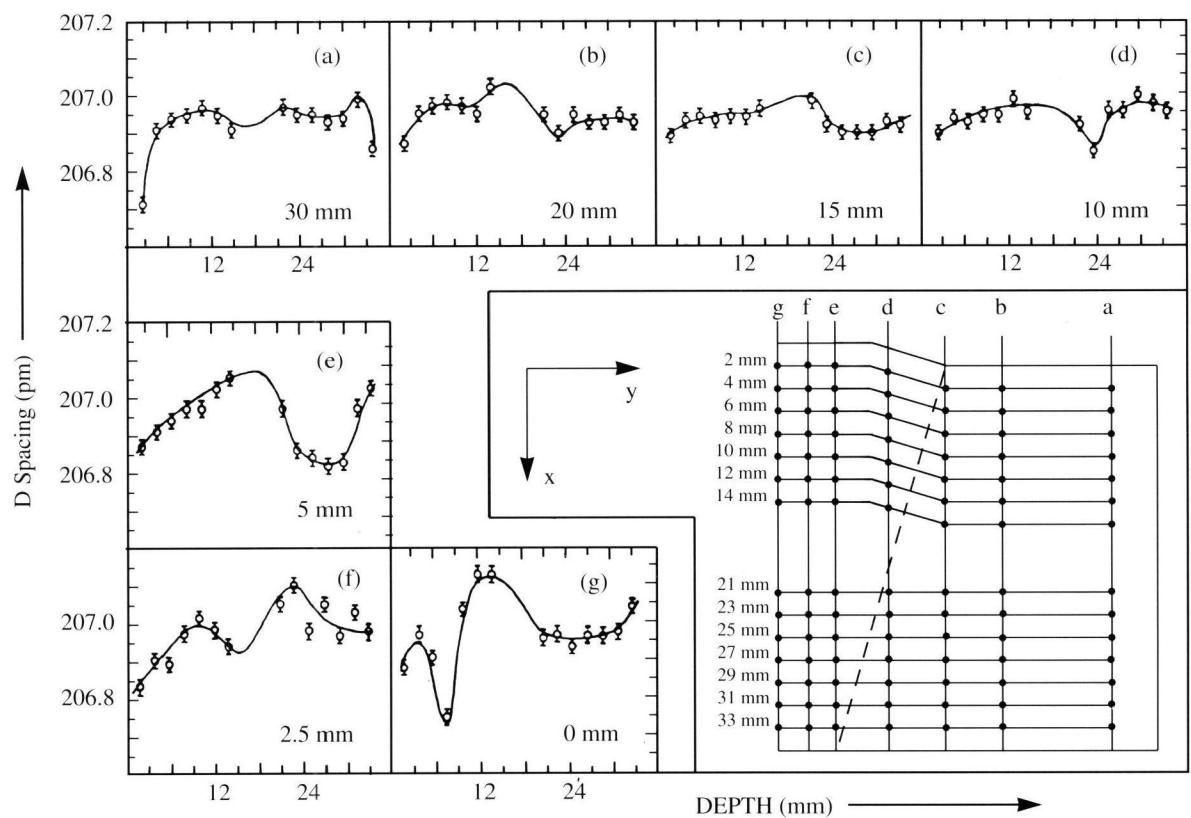


Fig. 5:

D_{111} values vs. depth of the sampling volume, along the lines a-g of the insert. Distance from the weld center: $y = 30$ mm (a), 20 mm (b), 15 mm (c), 10 mm (d), 5 mm (e), 2.5 mm (f) and 0 mm (g). Lines are guides for the eye.

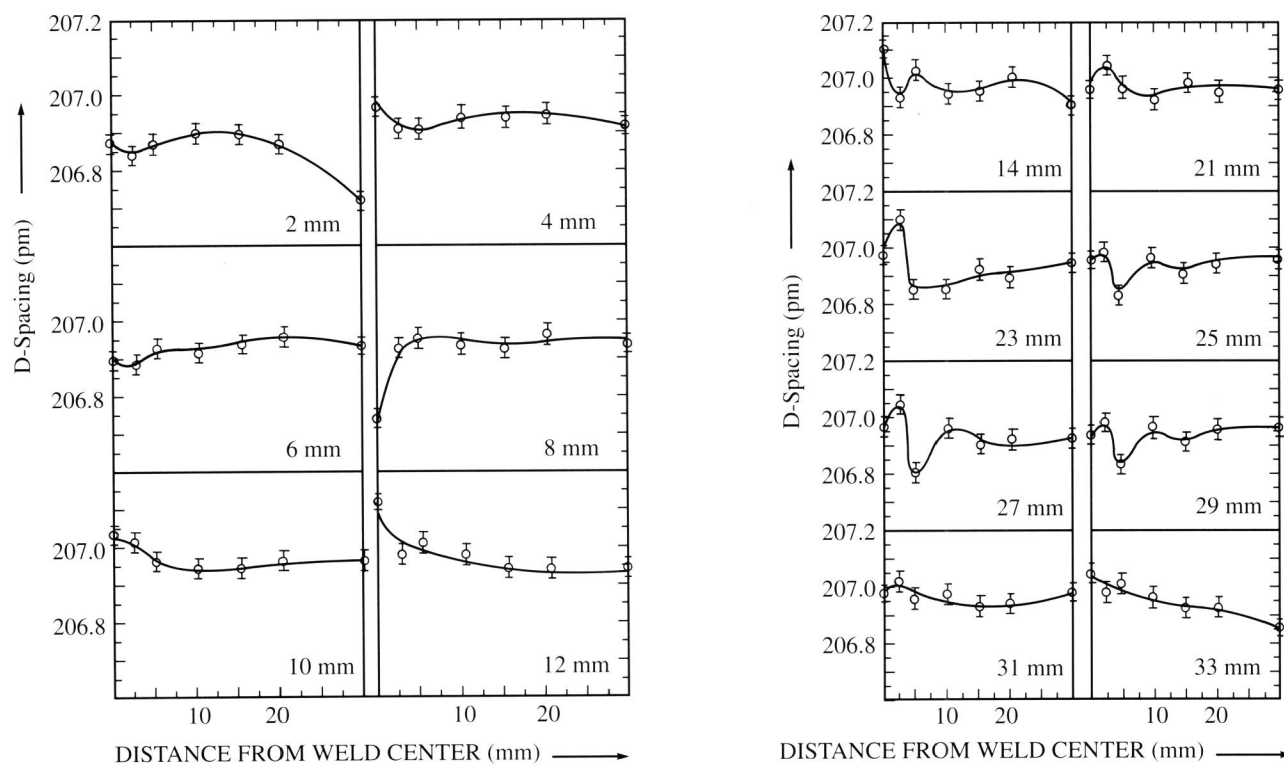


Fig. 6:

D_{111} values vs. distance from the weld center, at the different explored depths (see insert of Fig. 5). Lines are guides for the eye.

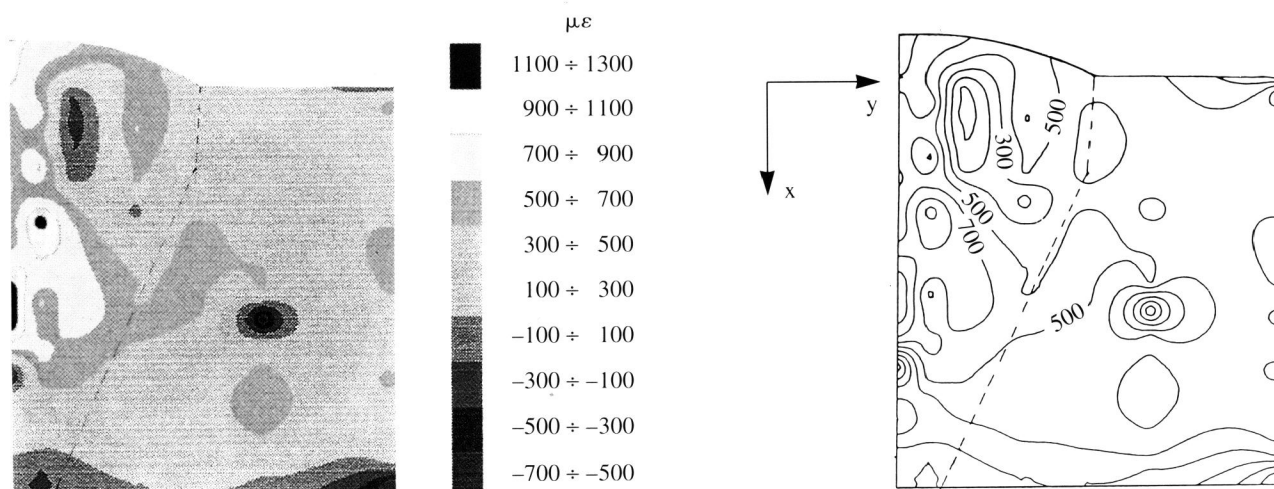


Fig. 7:

Map of the iso-strain levels ($\mu\epsilon$) in the $z = 85$ mm plane (111-diffracting plane, x-direction).