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INSIDE WELDS: ADVANCED CHARACTERIZATION OF RESIDUAL STRESSES BY NEUTRON DIFFRACTION

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Welding processes involve often very high temperature gradients, which can induce elevated residual stresses (RS). It is essential, therefore, to know these RS, especially by determining them experimentally e.g. before and after thermal treatments. Neutron beam techniques contribute in general to the solution of important questions and problems related to the methodological restrictions of the analysis systems normally used: complementary to these investigation methods, they provide concrete and fundamental help to optimize the finished industrial product and increase its performance. Neutron diffraction, in particular, is a powerful tool to assess in a non destructive and non invasive way the RS status in materials and components of technological interest. In this paper, the basic theoretical aspects and some examples are reported, regarding the possible determination of RS by using neutron diffraction in different kinds of welded structures. 39 Ref., 7 Fig.

Key words: residual stress, neutron diffraction, welded joints, advanced characterization

1. Introduction

In diverse industrial sectors involving welded joints, the requirements to rise materials and products performances, correspond with market needs and protect more and more public safety and environment, make pressure for continuous innovation and technological adaptations.

During the welding process, steep temperature gradients occur, generating thermal stresses large enough to produce plastic deformation as shape misfits between dissimilar regions of the joint's material. Phase transformations at different times in different locations of the joint can be also induced. From these non-uniformities in temperature, very significant RS – usually, large tensile residual macrostresses (RMS), sometimes of the order of magnitude of yield strength of the materials being joined – can be developed in solidification. Since RS are the stresses occurring in the non-existence of any external load or force (excluding the gravity), they must balance to zero within a component, stresses of one sign being equalized by stresses of opposite sign elsewhere. Surface RS, in particular, can be either tensile or compressive, depending on size and sign of the volume change with transformation. As the welded material solidifies due to the involved temperature gradient, it cools and begins to contract. The fluid in unsolidified regions cannot support stresses and accommodates the contracting surrounding areas. When this material later solidifies, it will try to contract more than the cooler zones around it, leading to RS, as schematized in a general sense in Fig. 1.

RMS in welding also lead to problems of distortion and dimensional control in components [1]. Significant levels of RS are developed, in particular, in the production of thick-section steel welds [2]. Intercrystalline and intergranular stress corrosion cracks, e.g., can occur in tanks and pipeline narrow welded zones, and they are due to the RS produced by the construction technique, and to the presence of aggressive elements [3]. It is of primary importance, therefore, to be able to determine experimentally these stresses and their eventual relaxation following heat treatments, assumed that calculation techniques, such as those based on the finite element method (FEM), are not fully reliable in all cases.

Knowledge of the real performing conditions of welded joints and the effect on material behaviour due to RS and other nano(micro)structural factors should play a crucial role also in the planning phase of a welding process and in the debugging of new welding project methods [4].

Various techniques exist to determine RS but few of them offer the capability to assess completely the RS spatial distribution through the thickness. If the stress distribution does not change (constantly along the welded seam), RS must conform the equilibrium relation:

$$\int_A \sigma_{ij} dA = 0 \qquad (1)$$

where A is the area over which the stresses will balance to zero. The smallest dimensions of this area define a

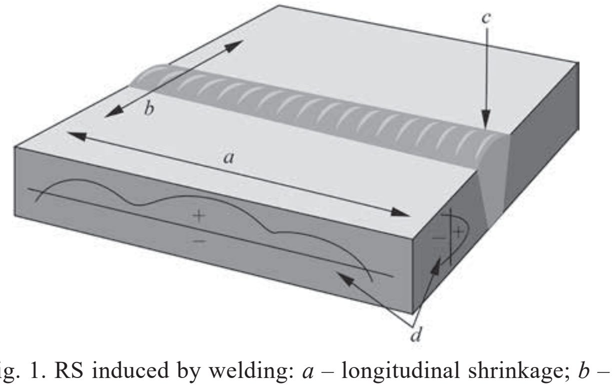

Fig. 1. RS induced by welding: *a* – longitudinal shrinkage; *b* – transverse shrinkage; *c* – weld seam; *d* – stresses

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characteristic length which can be adopted to delineate different types of RS. Since RMS are those that balance to zero when integrated over a cross section of a component, the characteristic length for RMS is on the order of the component's dimensions [1].

Some analytical and experimental methods determining RS in welded joints can provide good knowledge and understanding of the effects of component geometry (e.g., concerning thin welded joints, see [5–7]), welding process, thermal and mechanical properties, phase changes and transformation plasticity on the magnitudes and distributions of these RS. This can help studying the RS role in failure mechanisms, improving the existing techniques for reducing RS in sensitive locations and preparing standardised RS profiles useful to calculate the acceptability of defects in welded structures [8, 9].

Refined numerical modelling techniques are generally adopted, particularly in nuclear applications [10], to reproduce the welding process and to model the RS rise during welding, after post weld heat treatment (PWHT), after proof testing and in service under normal and abnormal operating conditions. Despite numerical modelling is a powerful instrument for RS calculation, also in this field of application a validation with reference to experimental results is essential [11].

Neutron beam techniques (NBT) are gaining more and more interest in industrial research and component diagnostics. Among the principal advantages, we can mention their non-destructive and non-invasive character and the possibility to investigate relative massive samples and components, due to the high penetration power of neutrons (order of centimeters in various engineering materials), as compared to other kinds of radiation (e.g., X-rays). Concerning the maximum sample dimensions for measurement in laboratory conditions, they depend on the neutron instrumentation being employed: one of the largest industrial component already investigated by ND, e.g., is the NiCrMoV wheel of an axial compressor for a heavy-duty gas turbine, having a diameter of 482 mm and thickness of 86 mm [12].

NBT results, eventually combined with simulation models such as FEM, can help knowing when failure is likely to occur and whether use of different materials and welding processes would produce a part or a structure that will last longer. NBT can also contribute in completing the database of structural nano(micro) investigations of welded joints and base materials, developing the nanoscopic safety criterion to forecast and prevent possible fracture processes in joints [13, 14].

Neutron diffraction (ND) has been already adopted to study non-destructively the RS profile through welds and joints and in adjacent zones. Nano(micro)structure, texture [15] and RS analysis can be studied in general by ND, and dedicated diffractometers are continuously developed involving a careful selection and optimization of the diverse mechanical and optical parts, based on intensive examination of the respective purposes.

2. Neutron Diffraction

Diffraction methods allow measuring both RMS and microstresses in crystalline materials, since each phase will have its own diffraction pattern supplying information on the stresses in that phase. Using ND to evaluate interplanar spacings in diverse directions, the complete strain tensor may be determined [16]. The main characteristics of ND measurements are:

- determination of the elastic strains only and of one component of the elastic strain tensor by each single measurement;
- strains can be converted to stresses using appropriate elastic moduli;
- selective determination only from grains which are suitably oriented with respect to the scattering vector;
- strain values are averaged over those grains.

In the typical scheme of a strain measurement, a collimated neutron beam with a wavelength λ is diffracted by a polycrystalline sample, then it passes through a second collimator and reaches the detector. Both collimators slits define the investigated volume (see Fig. 2), whose cross section, generally, can be as small till 1×1 mm^2 or, in singular cases, smaller.

Neutron diffractometers (strain scanners) have in general two axes and include: a wavelength selection system (e.g., a bent perfect crystal focusing monochromator), a system of slits allowing sample volume to be estimated; an Euler's cradle, enabling different orientations of the sample and connected to an automated travelling table *xyz* allowing for sample positioning; a neutron multidetector or position sensitive detector, which isolates and localises neutron signals on a line or surface, allowing the full diffraction peak to be directly recorded at a certain angular interval; eventual auxiliary equipment to heat up and/or to stress the investigated sample. The resolution of these scanners derived from the full width at half maximum

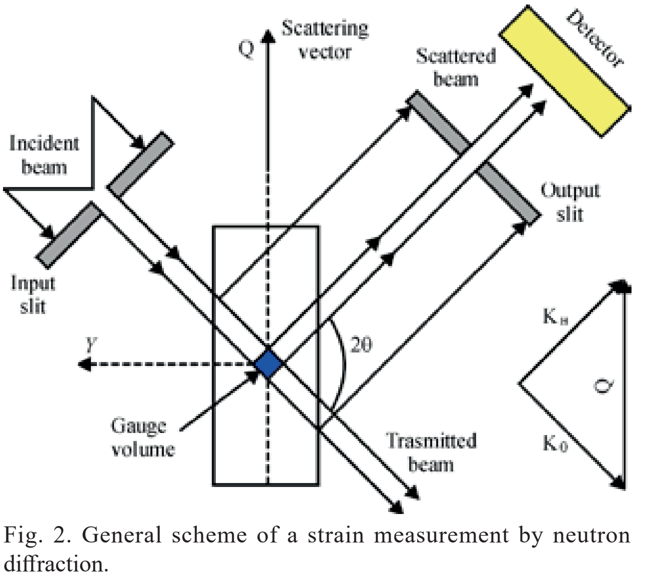

Fig. 2. General scheme of a strain measurement by neutron diffraction.

(FWHM) of the diffraction lines, nevertheless, is adequately high for small sample gauge volumes (when the width of the irradiated part of the sample is about 2 mm or less) but rarely better than $8\cdot10^{-3}$ for bulk samples, hence they are adopted to measure the elastic strain effects due to the variations of lattice constants and angular shifts of the diffraction lines. To analyse micro-strain effects resulting in a change of the FWHM and shape of broadened diffraction profiles, a significantly higher resolution is needed which can be achieved just by a 3-axis diffraction set-up recently proposed [17].

Concerning RS calculation, the Bragg law:

$$n\lambda = 2d_{nkl}\sin\theta \qquad (2)$$

(where the integer n is the diffraction order, 2θ is the ample take-off angle related to the maximum of the Bragg diffracted intensity peak, hkl are the Miller indices of the investigated lattice planes) allows calculating the lattice spacing d_{hkl}. The corresponding lattice strain is given by the relation:

$$\varepsilon_{hkl} = \frac{d_{hkl} - d_{0,hkl}}{d_{0,hkl}} = \frac{\Delta d_{hkl}}{d_{0,hkl}} = -\cot\theta_{hkl}\Delta\theta_{hkl} \qquad (3)$$

where θ_{hkl} is the diffraction angle and $d_{0,hkl}$ is the lattice spacing in a stress-free reference material. As the assessment of RS by ND is always related to the stress-free material state, a correct evaluation of the unstressed lattice parameters (e.g., the interplanar distance) is one of the key tasks, in order to avoid improper errors during the real material strain and stress evaluation. The accessibility of carefully measured zero-strain standards is also essential to confirm the absence of methodical instrumental effects determining the diffraction profile at a chosen scattering angle. The stress-free n particular, Some efforts are under way, hence, to develop new methods allowing more and more precise and practical evaluations of the unstressed lattice parameters, hence of the residual strains and stresses [18, 19]. Furthermore, at welding structural steels, phase microstructural transformations undergo in the fusion zone and in the HAZ. Each phase possesses its own lattice spacing and it is not known in advance in what volume the phase transformations have occurred. In ND measurements, hence, the microstructural phase composition, distributed non uniformly in the volume of welded joint metal should be taken into account.

The RS values can be obtained, in general, by knowing the elastic constants of the considered material and using the relations:

$$\sigma_{xx} = \frac{E}{(1+\nu)(1-2\nu)}(1-\nu)\varepsilon_{xx} + \nu(\varepsilon_{yy} + \varepsilon_{zz})$$

$$\sigma_{yy} = \frac{E}{(1+\nu)(1-2\nu)}(1-\nu)\varepsilon_{yy} + \nu(\varepsilon_{xx} + \varepsilon_{zz})$$

$$\sigma_{zz} = \frac{E}{(1+\nu)(1-2\nu)}(1-\nu)\varepsilon_{zz} + \nu(\varepsilon_{yy} + \varepsilon_{xx}) \qquad (4)$$

where σ_{xx}, σ_{yy} and σ_{zz} are the principal stresses, E is the Young's modulus and ν is the Poisson's ratio in an elastically isotropic model.

Uniaxial or biaxial RS are usually determined by ND as standard, and by rotating the triaxial component (4) RS can be determined with nominal accuracies of about ±30 MPa (e.g., in steel) and ±10 MPa (e.g., in aluminium).

In a ND analysis to determine RS, finally, peak shifts not associated to strain changes – i.e., pseudo peak-shifts or pseudo strains – should be avoided or corrected, as well as errors and uncertainties for measurements near surfaces eventually created by beam optics. Many possible systematic effects, indeed, may affect the interpretation of of ND data. For a full treatment of the theoretical bases, see ref. [1, 12, 16, 18–21].

3. Some application in the welding sector

Among the examples of application of ND to determine the RS profile, the following cases can be mentioned [22]:

– double-V welds – see, e.g., the analysis of a 50D C-Mn steel sample having dimensions of 13.5×240×42 mm (*x*, *y*, *z*), using the Bragg reflection (211), obtaining RS values along the *y* and *z* directions determined as function of coordinate *z*, in good agreement with conventional destructive method (strain gauge rosette);

– T weld – see, e.g., the analysis of a steel part from the offshore industry, in which deformation measurements in three directions were carried out for two series of point, confirming, as expected, the further away from the weld, the smaller the deformations;

– V welds – see, e.g., the analysis of an AISl 303 stainless steel part, with an investigated volume of 2.5×2.5×200 mm, using the (111) reflection to draw a deformation map.

RS measurements by ND have been performed before and after relaxation heat treatment in a 2.25Cr-1Mo ferritic steel arc welded pipe adopted for heat exchangers, having the following dimensions (mm): outside diameter = 218; internal diameter = 178; total length = 355. The 2.25 Cr1Mo steel is one of the most extensively used and best characterised grade among the chrome-molybdenum steels: it is generally used in steam generators and it is often preferred to austenitic steels, since its reduced weldability problems. Exercise temperature and pressure ranges are respectively 350-540 °C and 100-200 bar. Points of the pipe have been investigated at the following depth (mm): 2.5; 5; 7.5; 10. Fig. 3 shows the considered welded pipe during the analysis.

Fig. 4 represents hoop RS before and after the relaxation heat treatment (5 mm depth).

The gap between the RS values self-explains the resulting deviation trend between heat treated and not heat treated material [23]. An asymmetric progression of RS appeared across the welding: values shifted in high passing from one hand to the other of the weld zone, following the passes direction. Such trend can be ascribed to the asymmetry of the welding process, scheduling in the fibre the latest to cool a greater tensional level in comparison with the adjacent regions. RS after the heat treatment appear nothing along the radial direction, while along the axial one they are lower than before the heat treatment, exhibiting a mono-dimensional status [24].

Two 2.25CrlMo butt welded steel plates (A and B) have been investigated by ND before and after welding by shielding metal arc. Strain measurements have been performed in the plate *A* (before welding) along the three main directions *x*, *y* and *z*, in 11 aligned points inside the material, at the following depths (mm): 6.25, 12.5 and 18.75. Low tensile RS (<100 MPa) resulted in each direction. From strain measurements carried out in two points of Plate B near the calking, low tensile (40 MPa) and very low compressive (–10 MPa) RS have been found, perpendicular and parallel to the calking respectively, uniform through the thickness. Post welding RS resulted to change their trend close to the weld bead, and a symmetrical behaviour has been observed in x and y RS components at the depths of 6.25 mm and 18.75 mm. In correspondence of the middle thickness (12.5 mm), the effect of welding on the RS field appeared lower, as compared with other depths. Analogous trends have been found for the z RS component. Results obtained by ND have shown a good agreement for two measured points in comparison with data from ultrasonic testing (UT) averaged through the whole thickness (see Fig. 5) [25].

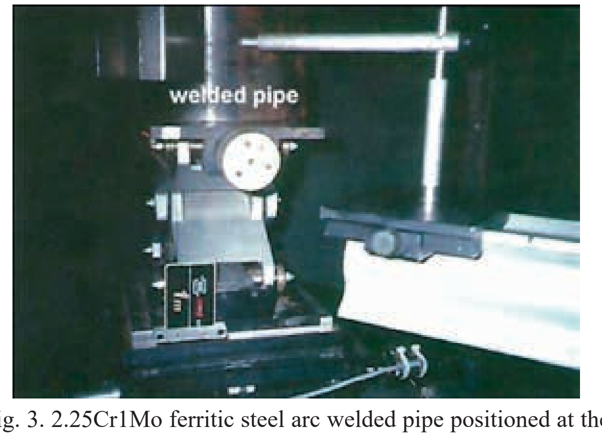

Fig. 3. 2.25Cr1Mo ferritic steel arc welded pipe positioned at the neutron diffractometer during the ND investigation (Image credit: Rogante Engineering Office)

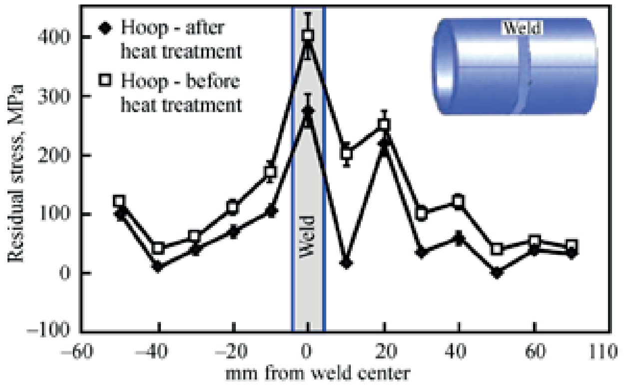

Fig. 4. Hoop RS (5 mm depth) determined by ND in a 2.25 Cr1Mo ferritic arc welded pipe before and after relaxation heat treatment

Fig. 6 is referred to the determination of residual micro-strains by ND in a pipe-flange welded joint made of steel.

A 2×2×5 mm^3 gauge volume was adopted, and the dimensions of the joint were the following (mm): thickness of the pipe wall = 8; diameter of the pipe = 100; thickness of the base = 12 [12].

In the Oil & Gas sector, the consistency of the several welded joints involved in a pipeline and the eventual occurrence of micro-cracks due to the welding processes can favour a yielding of the whole pipeline structure. A correct method to assess RS, in this case, is essential in achieving the desired safety and reliability levels. Some components of the combined total stress may exceed a particular design stress limit for the constitutive material of these pipelines, involving, thus, the risk of an early structural failure.

RS, consequently, represents a peculiar problem in pipelines, where their evaluation is usually performed through typical methods such as ultrasonic measurements, magnetic flux leakage or in-situ direct measurement of absolute levels of biaxial stress in ferromagnetic pipelines, based on magnetic anisotropy and permeability. This evaluation results difficult and incomplete, due to the lack of essential information related to the real state of the involved bulk material, which favours pessimistic estimates and risks of failures.

The correct assessment of RS levels performed by ND allows revealing the hidden cause-effect connections between the current condition of a given pipeline material under study and its potential failure modes under operating conditions. Knowledge of such relationships consents forecasting which types of failure modes

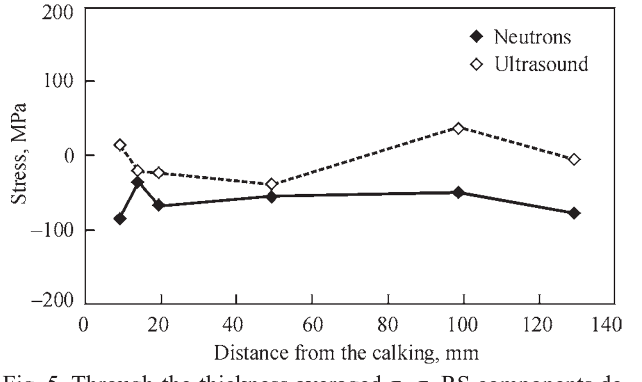

Fig. 5. Through-the-thickness averaged σ_x-σ_y RS components determined in a 2.25CrlMo butt welded steel plate by ND, compared with data obtained by UT

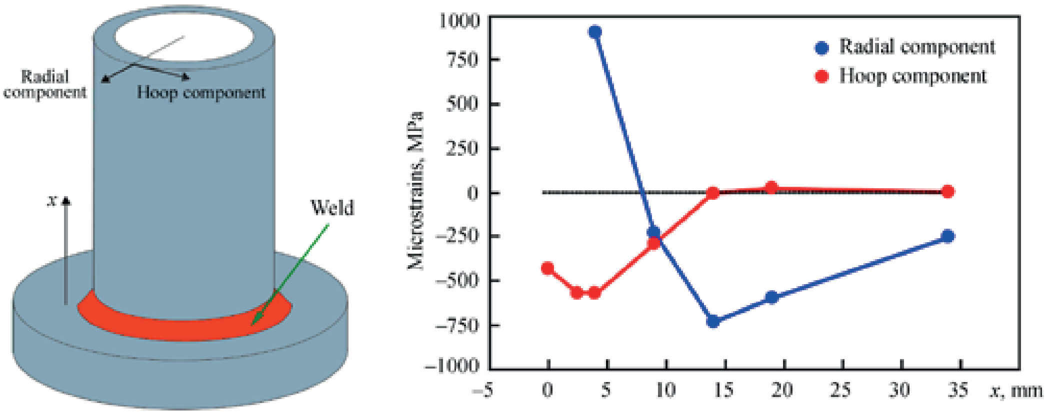

Fig. 6. Determination of residual strains by ND in a pipe-flange welded joint [12]

are likely to occur and the pipeline material resistance to crack propagation under operating conditions.

A feasibility study has been carried out by the Rogante Engineering Office (REO) on the determination of RS in pipelines. A failure predictive model has been proposed, in such work, based on nano(micro) scale level investigations and able to penetrate into the design and development procedure of pipelines. This model involves ND, to identify the cost-effective materials minimizing the production of RS, reducing stress-related failures and improving the pipelines reliability. It includes also the planning of a relational database formed by a collection of catalogued material parameters obtained also from ND for fresh samples which represent, statistically, the population of pipelines on which the forecasting tool is intended to be employed [23, 26]. Concerning the criteria of collecting samples for ND investigation, e.g., suggested dimensions concerning samples from pipe of large external diameter (> 500 mm) are reported in Fig. 7.

By cutting the original pipe to obtain the sample, a change occurs of the RS due to manufacture (not due to the welding process); before cutting the sample, consequently, it is necessary to apply extensometers at both the inner and the external surface of the pipe, to check the signal before and after cutting and record the RS alteration. Since thermal cutting of such samples adds heat-affected zone (HAZ) effects, the most adequate and less contaminating cutting procedure is grinding, also involving a cooling medium, to avoid temperatures ≥ 300 °C. Samples should be very precisely cut, to possess identical geometry with not more than 2 mm error in the sizes: the time necessary for sample alignment at the neutron instrumentation, consequently, would be reduced.

Another example of possible applications of ND concerns the railway sector, i.e. the determination of inner and sub-surface RS arising in the welds of structural connections of the frame of wagons [27].

A further possible application concerns the welding of steels as constitutive materials of moulds, for their repair. The welding processes usually adopted in this case are manual metal arc welding (MMA), tungsten inert gas welding (TIG), laser beam welding (LBW) and electro-spark deposition (ESD). In planning these processes, it must be taken into account that they generally implicate high temperature gradients from which both undesirable metallurgical modifications in the portions affected by the heat contribution and RS are created. The thermal gradients originating during the shrinkage, in particular, would lead contiguous areas of material to simultaneously assume different lengths, but this is impossible. These zones, to maintain the same length at all times, must therefore be subjected to tensions – compression or traction, depending on the temperature gradient. Critical situations can arise, therefore, with the appearance of fixed deformations and even cracks. The latter can occur in correspondence with both the HAZ and outside that zone. An advanced characterization of such welds by NBT, therefore, can be beneficial since it contemplates the various parameters responsible for performance and quality, including inner and sub-surface RS stresses [28]. Similarly happens for the welding of cast irons [29].

The following other examples can be reported of ND investigation for RS determination: AISI 304 butt welded 28” pipe (two TIG passes, and lastly twenty-six SMA passes distributed on ten layers) [30]; X welded sample (50 D C-Mn steel), a fillet weld of a steel component for offshore applications [31]; Al-2219 welded plate (62×48×6.5 mm) for spacecraft industry [32]; determination of RS longitudinal to electron beam weld in a Ni-based superalloy

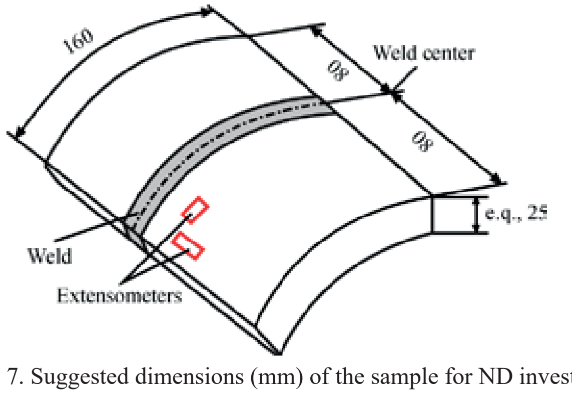

Fig. 7. Suggested dimensions (mm) of the sample for ND investigation. External diameter of the pipe > 500 mm

[33]; electron beam welded Ti-834 plate [34]; an Alloy 600 plate filled with three Alloy 82 weld beads, simulating a repair weld, in the frame of an international measurement round robin on an Alloy 600/82 multi-pass weldment [35]; near surface and inner RS around the weld toe of Weldox 1300 plates with a thickness of 15 mm, joined by robotic gas metal arc welding (GMAW) with Ar + 18% CO_2 as shielding gas [36]; fillet welds in 8 mm 900 MPa steel, with RS mapping perpendicular and parallel to the weld line and through the thickness in the vicinity of weld toe position [37]; bead-on-plate weldment, showing the significance of the weld start and end sites on the residual strain/stress distribution [38]; a rolled joint of a pressure tube made of three axial symmetric parts, modified SUS403 stainless steel as an inner extension, Zr-2.5Nb as the pressure tube and an Inconel 718 outer sleeve, to study the RS relaxation after a short-time aging treatment at 350 °C carried out to simulate thermal aging over the lifetime of an advanced thermal reactor at operating temperature [39].

Further applications concerning RS determination by ND in manual metal arc repair, alumino-thermic and friction-based welds are reported in [20].

Conclusion

A huge amount of work has been performed on the field of welded joints and materials weldability, to solve standard issues present in welding manufacturing [4]. The increase of the investigation in welds is fundamental to develop a correct design and weldment performance, with the main aim to improve strategies for prolonging component and plant lifetime.

The ND method is of great interest to specialists in welding, since it allows determining the distribution of RS over the thickness of different types of structural elements. There are high potentials that the ND method will make it possible to determine the complex RS state, which is formed during multipass welding of thick-walled elements made of steels with structural phase transformations. ND, indeed, has shown to be a valuable tool both to advance new joining processes and to enhance more traditional techniques. This method is also capable to validate FEM adopted for weld process optimization, to study in-situ post-weld heat treatments and to analyse the result of phase transformations during welding.

Since the thermal treatment due to the welding process influences also the nano(micro)structure, moreover producing the growth of some inclusions (e.g., precipitates), another NBT, i.e. small angle neutron scattering (SANS), is indicated to complete the analysis of welded joints: by knowing their chemical nature, it allows obtaining key characteristics of these defects (e.g., number and size distribution).

For industrial applications of NBT, the REO has long been developing dedicated methodological approaches with appropriate processing and treatment procedures of data from neutron measurements, including those for RS assessment in welding.

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МЕТАЛ ШВІВ: УДОСКОНАЛЕННЯ МЕТОДУ ОЦІНКИ ОСТАТОЧНИХ НАПРУЖЕНЬ ЗА ДОПОМОГОЮ НЕЙТРОННОЇ ДИФРАКЦІЇ

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Процеси зварювання часто включають дуже високі градієнти температури, які можуть спричинити підвищені залишкові напруження (ЗН). Тому важливо оцінювати величину ЗН, особливо шляхом їх експериментального визначення, наприклад до і після теплових обробок. Методи нейтронного пучка в цілому сприяють вирішенню важливих питань та проблем, пов'язаних із методологічними обмеженнями систем аналізу, які зазвичай використовуються. Вони забезпечують конкретну та фундаментальну допомогу для оптимізації промислового процесу та підвищення його продуктивності. Зокрема, нейтронна дифракція є потужним інструментом для неруйнівної та неінвазивної оцінки ЗН у матеріалах та компонентах, що представляють технологічний інтерес. У цій роботі наводяться основні теоретичні аспекти та деякі приклади щодо можливого визначення ЗН за допомогою нейтронної дифракції в різних видах зварних конструкцій. Бібліогр. 39, рис. 7.

Ключові слова: залишкові напруження, дифракція нейтронів, зварні з'єднання, передові методи досліджень

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