Journal of the Technical University of Gabrovo
https://mc04.manuscriptcentral.com/jtug

COMPARATIVE NEUTRON DIFFRACTION STUDY OF RESIDUAL STRESSES, ARISING AFTER ELECTRON BEAM WELDING OF VARIOUS STEELS

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ARTICLE INFO

Article history:
Received 30 September 2021
Accepted 1 December 2021

Keywords:
electron beam welding; steels; residual stresses; neutron diffraction

ABSTRACT

Electron beam welding is a technology in which residual stresses are formed as a result of temperature gradients. Neutron diffraction method allows the measurement of residual stresses in a high depth without destruction of the material.

In this report, we present a comparative study of the residual stress distribution at electron beam welding carried out with approximately the same linear energy of three types of steel. Structural steel, stainless steel and pressure vessel steel, as well as a sample of welded pure copper and stainless steel were studied. Minimal residual stresses were obtained in the electron beam welded pressure vessel steel, which has the lowest coefficient of thermal expansion.

INTRODUCTION

Steel is a widely used material in a number of industries [1]. There are many varieties of steel, which are obtained by varying the amount of carbon and other elements [2]. The formation of a monolithic joint from two steel parts or a steel part and a part of another metal or alloy can be done by welding. Currently, electron beam welding (EBW) receives a lot of attention among the welding techniques. This method has a number of advantages over other welding methods, such as the formation of a deep weld with a very small width, the formation of a joint without impurities of additives and without residues of inert gases, the formation of a joint with a minimal amount of defects and residual stresses [3,4]. Nowadays, the researchers based their investigations on the optimization of the technological conditions of EBW, to obtain welded joints with sufficient wear resistance, strength, and durability. Important for the durability of parts that operate under multiple loads are the residual stresses that occur due to the EBW. It is known that the EBW procedure is characterized as a highly non-equilibrium process due to the high-temperature gradients and very high heating and cooling rates. This leads to the formation of residual tensile and compressive stresses in the solidified metal and the heat-affected zone around it. Residual stresses are unavoidable during welding [5], but under appropriate technological conditions, they can be reduced significantly. One of the ways to measure and evaluate the residual stresses in EBW is the method of neutron diffraction [6,7]. Its main advantage is the ability to perform the measurements with sufficient accuracy, at a significant depth without destroying the material. This is achieved due to the high penetration level of the neutrons.

In this paper, we present a comparative study of the residual stress distribution at electron beam welding with approximately the same linear energy of three types of steel. Structural steel, stainless steel, and pressure vessel steel, as well as a sample of welded pure copper and stainless steel, were studied. The residual stresses were measured using the neutron diffraction technique.

NEUTRON DIFFRACTION METHOD FOR EVALUATION OF RESIDUAL STRESSES

The neutron diffraction technique is a powerful tool for the determination of residual stresses. This technique allows investigations in deep due to the high penetration level of the neutrons. Also, other advantages can be mentioned, such as non-destructive character, good spatial resolution, the method allows and investigation of the microstrain, dislocation density, crystallite size, etc. [8].

The presence of residual stresses in the material leads to a deformation in the crystal lattice and, accordingly, the interplanar distance d_{hkl} changes relative to the distance d_{hkl}^{0} in the stress-free state. The principal for the determination of the interplanar distances is based on the Bragg's low, which can be written according to formula (1):

$$2d_{hkl}\sin\theta_{hkl} = n\lambda \,. \qquad (1)$$

In (1) n is an integer, λ is the wavelength of the incident radiation, d_{hkl} is the interplanar distance, and θ_{hkl} is Bragg's angle. The deformation of the crystal cell ε_{hkl} as a

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result of the residual stresses is expressed by the following equation:

$$\varepsilon_{hkl} = \frac{d_{hkl} - d^0_{hkl}}{d^0_{hkl}} . \quad (2)$$

As can be seen from equation (1), the diffraction maximum condition depends on the wavelength and the scattering angle.

In the case of pulsed neutron sources, the TOF method (Time of flight) is applied.

The time of flight of the neutron from the source to the detector is determined by the distance L and its speed v:

$$t = \frac{L}{v} \quad (3)$$

From the relation of the de Broglie wavelength to the velocity of the particle $v = \frac{h}{m\lambda}$ and from (1)

$$t = \frac{2mLd_{hkl}\sin\theta}{h}, \quad (4)$$

where h is the Planck's constant.

It can be seen that at constant values of the Bragg's angle the time of flight of the neutron depends only on the interplanar distance and the change of this time in the deformed state can be used to measure the deformation:

$$\varepsilon = \frac{\Delta t}{t} \quad (5)$$

For measured strain values, stresses are calculated using Hooke's law and known elastic constants (Young's modulus and Poisson's ratio) for the respective material.

MATERIALS AND WELDING APPROACHES

Four samples made of three types of steel were studied - structural steel with designation 14NiCr10 (1.5732) according to German standard DIN-EN, stainless steel with designation X5CrNi18-10 (1.4301) according to German standard DIN-EN and pressure vessel steel with designation 18MND5 according to the French standard ANFOR NF. The chemical composition of the three types of steel is presented in Table 1.

The thermophysical parameters of the studied types of steel are presented in Table 2. The density ρ [kg/m^3], the specific heat capacity C [J/(kg.K)], the thermal conductivity coefficient λ [W/(mm.K)], the melting point T_{melt}. [ºC] and the expansion coefficient a [10-6 1/K] are included in the table.

The technological parameters of the EBW are presented in Table 3. The accelerating voltage U [kV], the beam current I [mA], the welding speed v [mm/s] and the linear energy Qlin. [J/mm] are indicated. The linear energy was calculated as a ratio of the beam power and the welding speed and it shows the input energy per unit length.

Table 1 *Chemical composition of the studied steels in weight percentages*

	C	Si	Mn	Cr	Ni	P	S	Mo	V	Cu	Fe
14NiCr10	0.11	0.27	0.6	1.35	3.25	≤0.025	≤0.025	-	-	-	Bal.
X5CrNi18-10	0.08	1	2	18-20	8-10.5	0.045	0.03	-	-	-	Bal.
18MND5	0.18	0.25	1.6	0.17	0.64	-	-	0.61	0.12	0.13	Bal.

Table 2 *Thermophysical parameters of the studied steels*

	λ, W/(mm.K)	*ρ*, kg/m^3	*C*, J/(kg.K)	$T_{melt.}$, ^oC	*α*, 10^{-6} *1/K*
14NiCr10	0,0270	7680	540	1410	15,3
X5CrNi18-10	0,0215	7920	500	1450	17,3
18MND5	0,0520	7800	470	1508	13,7

Table 3 *Technological parameters of the EBW*

	Material	*U*, kV	*I*, mA	*v*, mm/s	$Q_{lin.}$, J/mm
sample 1	12XH3A	60	50	10	300
sample 2	X5CrNi18-10	60	50	10	300
sample 3	X5CrNi18-10 and Cu	55	50	10	275
sample 4	18MND5	150	20	10	300

The measurements of the residual stresses were performed in the Frank Laboratory of Neutron Physics of JINR (Dubna, Russian Federation) using FSD diffractometer located on channel 11a of the IBR-2 pulsed reactor. This diffractometer has been specially developed for the study of stresses in bulk samples [8,9,10].

RESULTS

Figures 1-4 show the results for the residual stresses of the considered specimens. Alternating tensile and compressive stresses are observed. The results show that in the middle of the joint, mainly tensile stresses with maximum values were formed. The maximum values of the residual stresses are along x-component in structural and stainless steels. In pressure vessel steel, the maximum value in the center of the seam is seen for the z-component. For samples 1, 2, and 3 there is a clear difference in the distribution of residual stresses for the individual components, with the highest values for the x-component, followed by the y-component and the lowest for the z-component. As move away from the seam, the differences in the three components decrease. In sample 4, the z-component has the largest value in the middle of the seam, the y-component has the average value and the x-component has the smallest value. In the range from 2 mm to 4 mm away from the seam, this dependence is reversed and the trend is the same as for the other samples. In sample 4, a minimum value of tensile stresses was measured in comparison with the other samples - this value is 180 MPa. For sample 1, the maximum value is the highest among all considered specimens - it is 680 MPa. For samples 2 and 3, tensile stresses with maximum values of 450 MPa and 400 MPa, were obtained. For all considered specimens, the maximum compressive stresses do not exceed -100 MPa. The comparison of the residual stresses in samples 2 and 3 shows that the influence of copper in sample 3, obtained by welding a copper plate and a stainless steel plate, is quite weak and does not lead to significant differences in the distribution of residual stresses compared to sample 2, which is welded from two identical stainless steel plates.

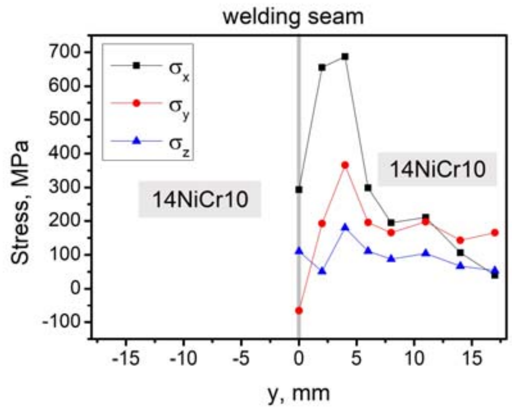

Fig. 1. Residual stress distribution for sample 1 - structural steel 14NiCr10

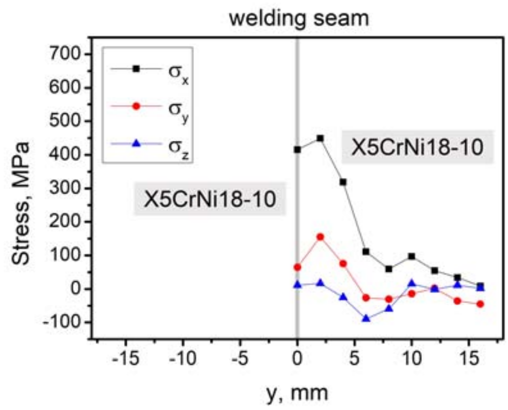

Fig. 2. Residual stress distribution for sample 2 - stainless steel X5CrNi18-10

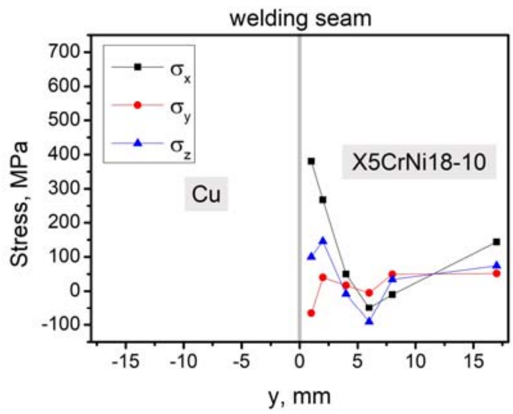

Fig. 3. Residual stress distribution for sample 3 - stainless steel X5CrNi18-10 and pure Cu

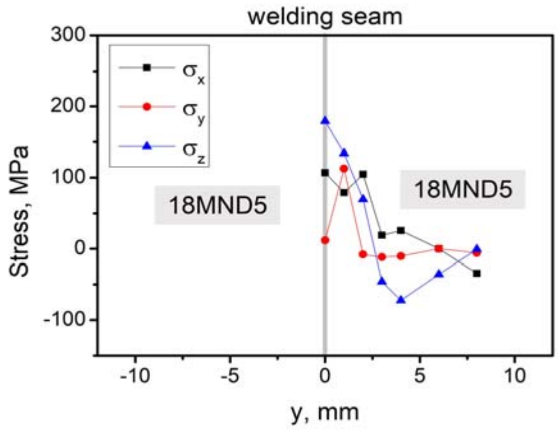

Fig. 4. Residual stress distribution for sample 4 - pressure vessel steel 18MND5

DISCUSSION

The basis for comparison of the residual stresses at EBW of the tested samples is the same or almost identical linear energy with which they were welded. Obviously, the differences in the distribution of residual stresses are due to the different thermophysical properties of the studied steels, which are summarized in Table 2. The coefficient of thermal expansion is an important thermodynamic characteristic of crystalline materials, showing the change in the lattice parameters and the volume of the unit cell. Lower coefficient of thermal expansion leads to a weaker change in the structural parameters of the unit cell and vice-versa. Therefore, joint of welded materials with lower thermal expansion coefficient should exhibit lower amount of residual stresses, which is in agreement with our results. The lowest amount of residual stresses was found at the joint of the 4th specimen.

CONCLUSION

Welding joints of three types of steel - structural, stainless and pressure vessel steel, are obtained by EBW with the same linear energy. The neutron diffraction method has been successfully applied to determine the residual stress distributions in different welded materials. It is clearly shown that the residual stress values depend on the thermophysical properties of steel. Maximum residual stresses (680 MPa) were measured for structural steel, and minimum (180 MPa) - for the pressure vessel steel, which has the highest coefficient of thermal conductivity and the lowest coefficient of thermal expansion.

ACKNOWLEDGMENTS

This work was supported by the Bulgarian Nuclear Regulatory Agency and Bulgarian Ministry of Education and Science (contract D01-368/18.12.2020).

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