XVII Konferencja Naukowo-Techniczna
TKI2024
TECHNIKI KOMPUTEROWE W INŻYNIERII
15–18 października 2024

Theoretical and experimental analysis of thermomechanical states in butt welded steel flat bars

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ABSTRACT: In the paper, an experimentally confirmed methodology for analysing thermomechanical states and, consequently, predicting the final state of the material in the form of structure and residual stress distributions is presented. As part of experimental tests, a butt-welded joint of two flat bars made of S235 steel using submerged arc welding (SAW) was performed. The SAW method allows for obtaining a relatively smooth weld face, which enabled using the MAGSTRESS5C device using the Barkhausen effect with a rotating magnetic field to measure stress. Then, macro- and micro-structural metallographic tests and hardness measurements were carried out. Numerical simulations of thermomechanical states were performed using proprietary programs developed in the Borland Delphi environment based on analytical descriptions of the temperature field, kinetics of phase transformations and stress states. The calculations assumed the welding technological parameters used in the experiment. The calculation results were illustrated with the distribution of temperature, structure, strains and stresses in the central cross-section of the welded flat bars. A detailed analysis of the thermomechanical states at selected cross-section points was performed. The calculated values of residual stresses were compared with the results of experimental measurements, and satisfactory agreement was shown.

Keywords: welding; butt joint; temperature field; stress measurement; residual stresses

1. Introduction

In this paper, a methodology for the analysis of thermomechanical states based on analytical descriptions of the temperature field, the share of structural components, strains and stresses, confirmed by metallographic tests and stress measurements, is presented. The calculations were carried out using proprietary programs created in the Borland Delphi environment based on our own algorithms. The included illustrative material regarding the states in the cross-sections of welded elements and a detailed analysis of these states at selected points in these cross-sections allow for tracing the changes occurring in the material during the entire welding process.

2. Experimental research

The analysis involved the butt welded joint of S235 steel flat bars with a thickness of 12 mm, width 10 mm and length of 1000 mm each. Before welding, the sheets were beveled to obtain a welding groove (Fig. 1).

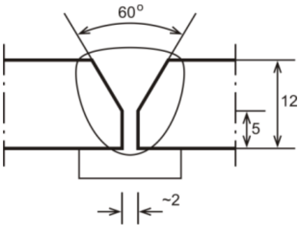

Fig. 1. Scheme of the butt welded joint of flat bars with welding groove

The welding process was carried out with a submerged arc welding in which the welding parameters were as follows: voltage U = 30 V, current I = 600 A, welding velocity v = 20 m/h, and the heat input Q = 3,24 kJ/mm. The Submerged Arc Welding method allows for obtaining a relatively smooth weld face. This, in turn, allowed the use of the MAGSTRESS5C, which uses the Barhausen effect with a rotating magnetic field to measure stresses. Measuring longitudinal stresses on the top and bottom surfaces of welded flat bars were made halfway along their length in a line perpendicular to the welding direction. Metallographic analysis (Fig. 2) was performed using a microscope Olympus GX51 and the hardness test was carried out using Qness 60A+Evo.

Fig. 2. Scheme of the butt welded joint of flat bars with welding groove

3. Calculation of thermomechanical states

Calculations of the temperature field of single-sided welded flat bars with full penetration were carried out based on the model described in [1]. The three-dimensional temperature field was determined assuming a Gaussian distribution of the heat source.

The temperature field varying in time and space results in phase transformations, strains related to thermal expansion and changes in the mechanical properties of the material. The quantitative assessment of the shares of structural components (austenite, ferrite pearlite) was made on the basis of descriptions and models of the kinetics of phase transformations contained in [2].

The methodology and models presented in [3] were used to calculate thermal and structural deformations. The analysis of stress states was carried out based on the model of non-isothermal plastic flow of steel [4], taking into account the influence of phase transformations.

The temperature-dependent material properties were modeled based on [5]. The stresses in elasto-plastic state are determined by iteration using the method of elastic solutions at the variable modulus of longitudinal elasticity conditioned by the stress-strain curve [6].

4. Results and discussion

Based on the maximum temperature values reached in individual areas of the welded joint, heat affected zones were determined (Fig. 3), defined by the temperature limit values of the liquidus T_L, solidus T_S and the end A_3 and the beginning A_1 of the austenitic transformation, respectively. Residual stresses (after cooling down) in the right half of the welded flats is in Fig. 4 presented.

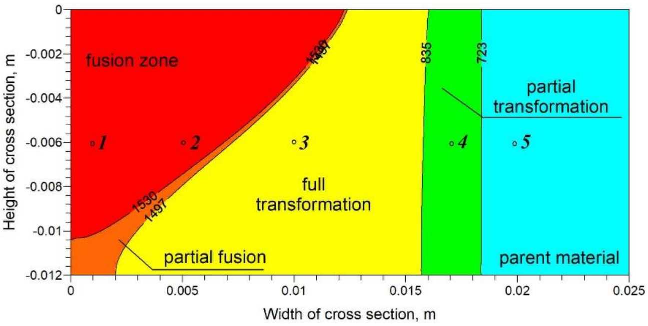

Fig. 3. Heat affected zones with marked points for which thermal cycles, phase transformations and stresses were analyzed.

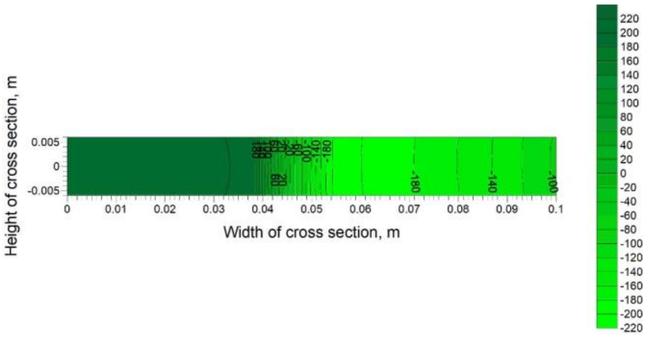

Fig. 4. Residual stresses (after cooling down) in the right half of the welded flats.

Verification of the calculated residual stresses by comparison with the measurement results using the Barhausen effect with a rotating magnetic field is shown in Fig. 5.

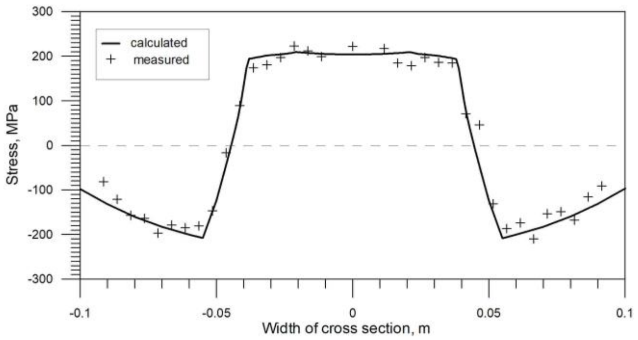

Fig. 5. Comparison of residual stresses calculated and measured on the upper surface of welded flat bars (from the weld face side).

5. Summary

The performed calculations and experimental tests provide the basis for formulating the following conclusions:

1) the presented approach to the problem of analyzing thermomechanical states allows taking into account the influence of phase transformations (changes in structure and structural strains),
2) the results of metallographic tests and measurements of residual stresses in the front connection of flat bars confirm the correctness of the used models of the temperature field, the kinetics of phase transformations and the calculation of strains and stresses,
3) developed models and programs based on analytical solutions allow for quick assessment of thermomechanical states at any point of the welded elements and at any time during the process,
4) the magnetic method using the Barkhausen effect is effective in determining stresses in flat and smooth surfaces; similarly to the penetrating radiation diffraction meth-od using X-rays (XRD), it does not provide reliable values for measuring stresses on the face and root surfaces of the weld.

Taking into account the effect of phase transformations in the modeling of stress states allows for a full analysis of the phenomena occurring in the welded joint.

References

[1] Winczek J., Parkitny R., *Modelling of heat affected zone in submerged arc welding butt joint with thorough penetration*, Procedia Engineering, Vol. 177C, pp. 241–246, 2017.

[2] Winczek J. *The analysis of temporary temperature field and phase transformations in one-side butt-welded steel flats*. In Joining Technologies, 1st ed.; Ishak, M., Ed.; Intech: Rijeka, Croatia, 2016; pp. 113–140.

[3] Winczek J., Makles K., Gucwa M., Gnatowska R., Hatala M., *Modelling of strains during SAW surfacing taking into heat of the weld in temperature field description and phase transformations*. IOP Conf. Ser.: Mater. Sci. Eng., Vol. 225, 012038, 2017 doi:10.1088/1757-899X/225/1/012038.

[4] Winczek, J.; Yadav, A. Fundamentals of thermo-fluid-mechanical modelling in welding processes. In *Handbook of Welding: Processes, Control and Simulation*, 1st ed.; Silva, F.J.G., Bastos Pereira, A.M., Eds.; Nova Science Publishers, Inc.: Hauppauge, New York, USA, 2021; pp. 315 – 350.

[5] Winczek, J.; Mičian, M.; Ivanov, V. The modelling of temperature-dependent stress-strain curves for weldable steels, *J. Appl. Math. Comput. Mech.* **2018**, *17(3)*, 111-117.

[6] Winczek, J.; The analysis of stress states in steel rods surfaced by welding. *Arch. Metal. Mater*. **2013**, *58*, 1243 – 1252.