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Verification of Properties of Joints Made of Advances High Strength Steels in the Conditions of the Complex Thermal Cycles of the HPAW Process

Abstract: The article discusses the primary issue related to the verification of properties of joints made in AHSS in relation to conventional structural steels and based on the identification of cooling time $t_{8/5}$. The solution suggested in the study involving the application of the Finite Element Method is based on two computational models. In addition the article presents a material model allowing for properties of single metallic phases and their interaction during the welding cycle. The study also describes the numerical model of the HPAW (plasma + MAG) heat source composed of two models predefined in the Simufact.Welding software programme corresponding to the nature of constituent processes. The research-related tests also involved welding simulations and experimental verification. The tests demonstrated the conformity of simulation results and the high usability of simulation when verifying properties of joints.

Keywords: properties of joints, ddvances high strength steels, AHSS

Introduction

The analysis of the development of advanced structural steels implies the tendency of obtaining high strength without compromising the cost efficiency of material plasticity [1]–[3]. It will be possible to shape prefabricated elements of car bodies, cranes and superlight self-supporting structures. The making of such a material is not easy as it requires the maintaining of the low tolerance of the chemical compositions and the high regime of technological parameters of a complex metallurgical process. The welding of the above-named materials always leads to unfavourable changes in the precisely formed microstructure resulting in decreased strength. A heat input to a joint not impairing the heat affected zone is restricted within a very narrow range and requires precise calculations [4-5].

Verification of welded joint properties

The forecasting of properties of welded joints consists in the calculation of cooling time $t_{8/5}$ on the basis of technological and geometric parameters. The analytical determination of time $t_{8/5}$ requires the knowledge of, among other things, preheating temperature, heat input and material thickness [6]. Based on time $t_{8/5}$, using the CCT-W diagram, it is possible to identify the structural composition, hardness and strength of the heat affected zone.

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In cases of conventional structural steels having a yield point of approximately 355 MPa, the range of time $t_{8/5}$ is vast and amounts to tens of seconds. For this reason, in most cases the in-depth analysis of the HAZ properties is not necessary. In relation to AHSS, the range of time $t_{8/5}$ becomes narrow, with related tolerance amounting to several seconds [7]. It is then possible to demonstrate the inaccuracy of previous analytical methods resulting from the unprecise identification of linear energy (difficult-to-determine actual current parameters) or simplifications in calculations [8]–[10].

Time $t_{8/5}$ the temperature of the weld in the function of time using a thermocouple sensor immersed in the liquid metal pool [11]. However, the above-named method has its limitations. The first restriction results from the area of measurement (measurement result related to time $t_{8/5}$ in the weld axis will differ from that in the heat affected zone by several seconds) [5], whereas the second limitation is the laboriousness resulting from the necessity of performing the process in many variants.

The above-named problem can be solved by applying FEM-based prediction. In spite of the fact that the process requires the knowledge of many material parameters, the use of a precise heat source model and the work of qualified personnel competently using complex applications, it makes it possible to obtain the precise assessment of joint properties. The FEM-based analysis enables the fast creation of many variants of the process. In turn, the foregoing enables the faster and cheaper identification of an optimum welding technology [5], [12], [13].

Defining the weldability of martensitic AHSS

The high strength of AHSS is obtained through the presence of tempered martensite in the microstructure. The welding process provides a heat input inducing the further tempering of martensite and resulting in the loss of strength. The heat affected zone contains a certain area of tempered martensite constituting a soft zone. In previous tests, maximum width of the soft zone was defined as amounting to 25% of the material thickness related to the maximum decrease in the strength of the area amounting to 10% [14]–[16]. Below the above-named value, the joint is subjected to contact hardening eliminating the decrease in strength. The primary issue related to the weldability of AHSS is the maintaining of the appropriate size of the soft zone through the control of heat amount.

The numerical model of steel Weldox 1300 was performed using the Simufact.Materials software programme developed by the MSC Software company. The checkbox of material types is presented in Figure 1.

In the Simufact software programme, materials are defined as single and multi-phase ones. The latter allow for the effect of individual structural constituents (martensite, bainite, ferrite, pearlite and austenite) on properties. The non-linear numerical model of a material used
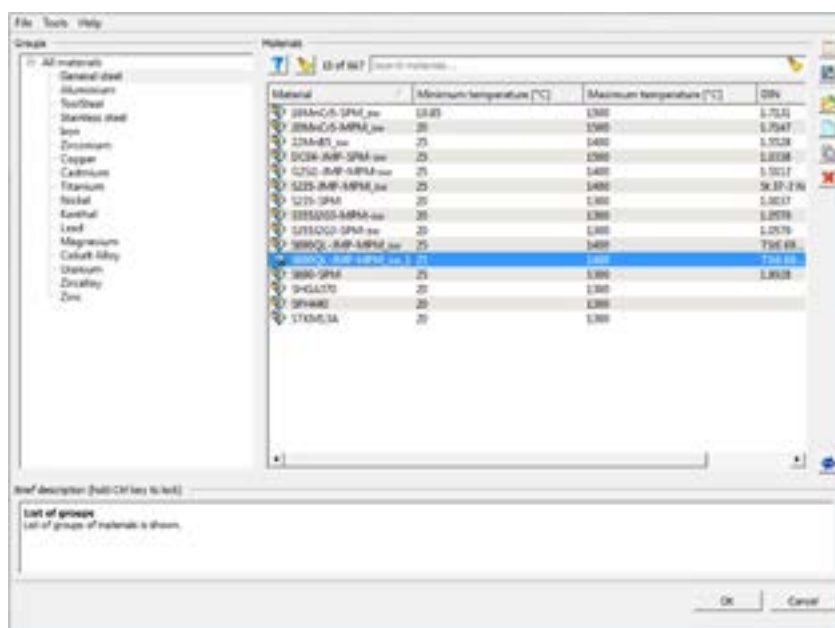

Fig. 1 Window of the Simufact.Materials programme containing the base of single-phase materials (SPM) and multi-phase materials (MPM); when performing welding simulations one can select materials with the "sw" extension (Simufact.Welding)

in welding process simulations should contain a considerable amount of information related to the wide range of properties in the function of temperature, including primarily:

– Young's modulus and Poisson ratio – calculation of stresses and displacements;

– thermal expansion and conductivity, specific heat – identification of heat flow and temperatures;

– flow curves – identification of plastic strains.

The above-presented properties were identified in relation to individual structural constituents of steel subjected to analysis. Resultant material properties were determined on the basis of the structural composition identified using the CCT diagram. Selected properties are presented in Figure 2.

The Simufact.Materials software programme makes it possible to edit data. Material-related data obtained using the simulator of thermal cycles were entered into the system using the table editing method (Fig. 2b). Data concerning curves of phase transformations were entered directly into the file of the material model in the XML format (Fig. 3). The definition created in the above-presented manner enabled the determination of temperature and structural composition at any area of the joint in the function of welding time (Fig. 4).

The time-related correlations of the temperature field and structural composition enable the identification of stresses, displacements, strains, hardness and time t8/5 at a predefined location.

Hybrid process implementation

A heat input to the material can be achieved in two ways. The first method involves the performance of low-current multiple-run welding. However, because of its laboriousness, the use of the method is not justified in terms of increased efficiency.

Another manner enabling the restriction of a heat input consists in increasing a welding rate and, to balance penetration, increasing the energy of the welding power source. In
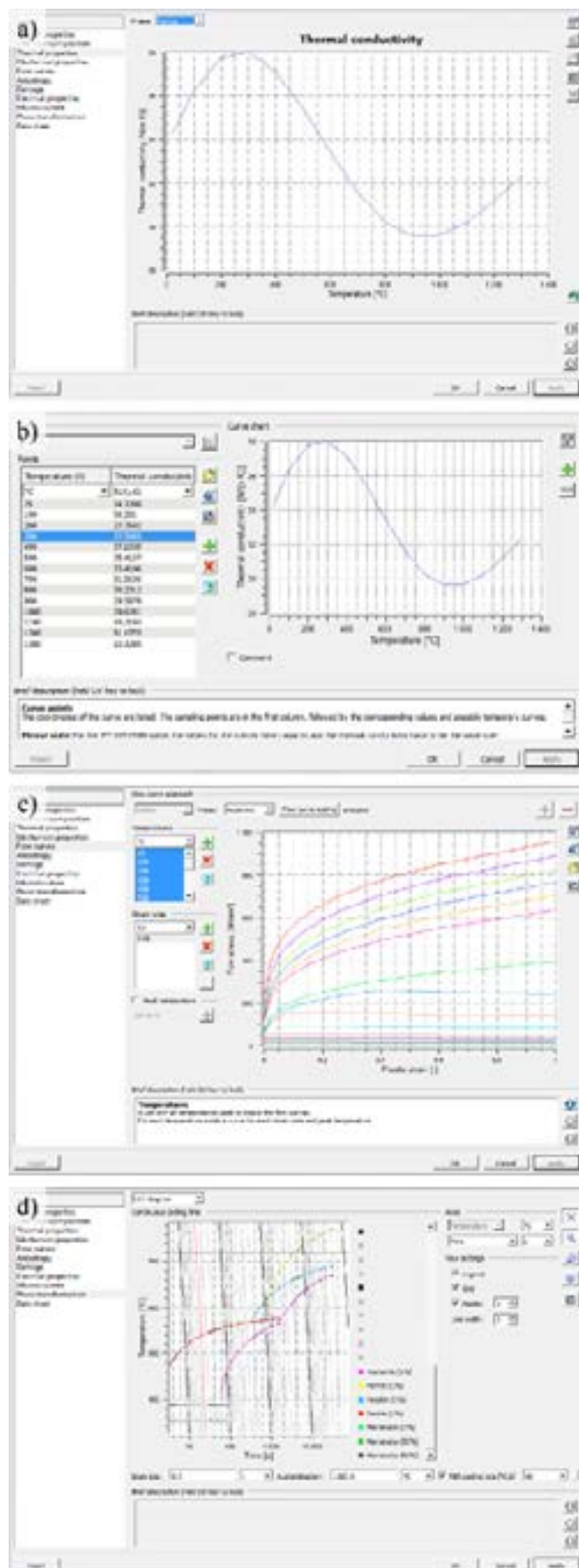

Fig. 2. Selected non-linear properties of the numerical model of the multi-phase material: a) ferrite thermal conductivity; b) editing a table presenting the thermal conductivity of ferrite in the function of temperature; c) austenite flow curves; d) CCT (continuous cooling transformation) diagram
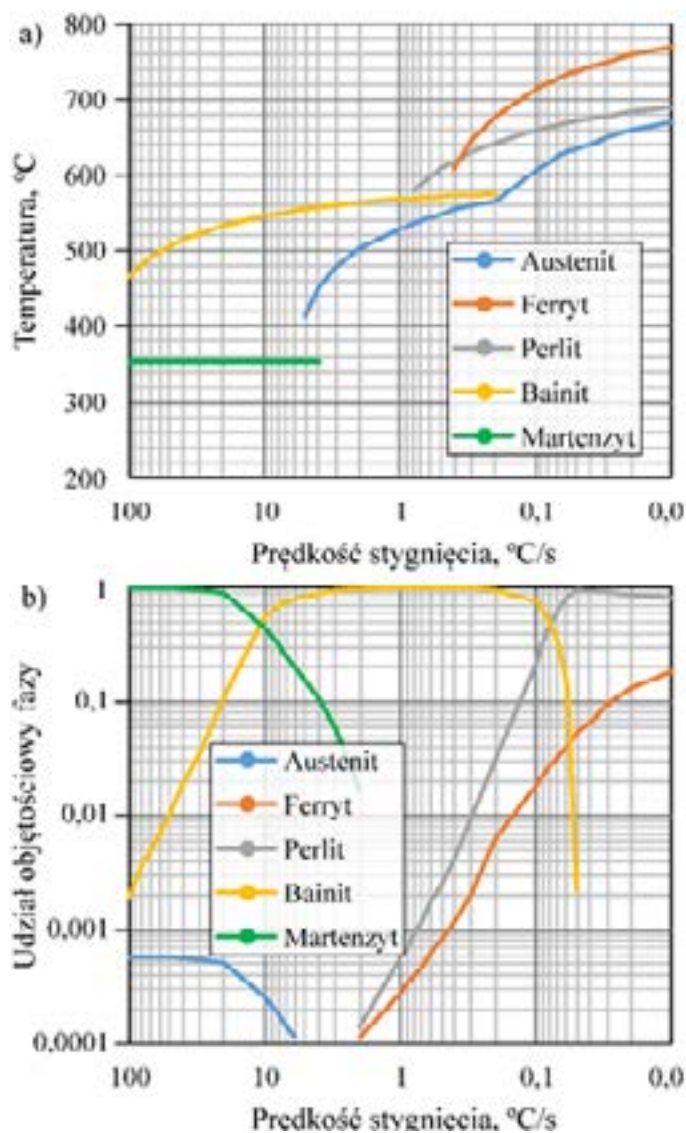
Fig. 3. Entering data for curves of structural transformations: a) structural transformations in the function of cooling rate; b) structural composition of the material in the function of cooling rate
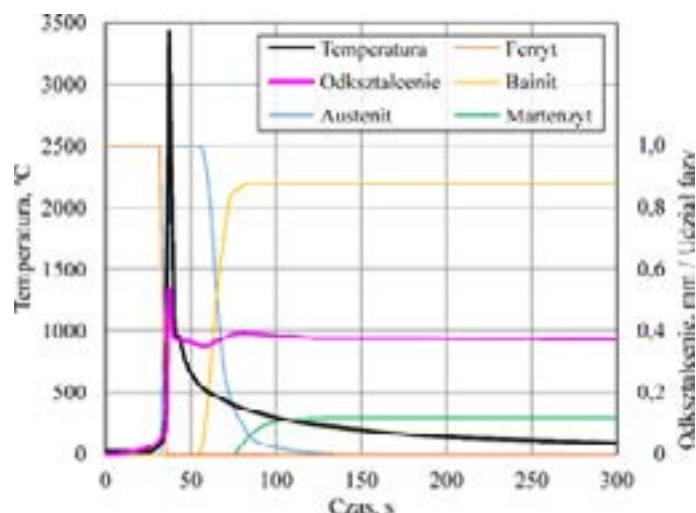
Fig. 4. Weld area-related FEM-based calculation results presenting welding temperature-triggered changes in the structural composition and strains

such conditions, high-current welding arc affects a given area for a significantly shorter time. A heat input is restricted by the thermal conductivity of the material, preventing the fast transfer of significant energy to the joint. Regrettably, a high welding rate results in an inconvenient manner in which the liquid metal pools cools down, thus triggering the segregation of low-melting eutectics and impurities in the weld axis.

A solution to the above-presented problem could be the application of multi-electrode welding or hybrid welding. One of the most popular hybrid welding methods is a process combining laser welding with the MIG method also known as Hybrid Laser Arc Welding

(HLAW). In spite of its popularity the process has two significant disadvantages, i.e. high costs and high quality of pre-weld edge preparation.

A competitive alternative to the HLAW process is Hybrid Plasma Arc Welding (HPAW), where laser has been replaced with plasma and the MIG process with the more efficient MAG method (Fig. 5). The process is characterised by low investment expenses and running costs as well as by certain fixing-related inaccuracy tolerance, important when welding large-sized load bearing elements.

Applications of the HPAW process require the narrow regime of welding parameters. The identification of parameters in production conditions is time-consuming and does not ensure the obtainment of optimum properties of joints. The numerical simulation-based prediction of parameters at an early production stage enables the proper making of joints.

The tests of the HPAW process involved the use of the Simufact.Welding software programme developed by MSC Software. The programme makes it possible to easily configure joints to be analysed. Regrettably, the programme does not feature the mesh generator to create the geometry of elements to be welded. The programme uses an external mesh generator (Midas NFX software programme) from which geometries were exported in the
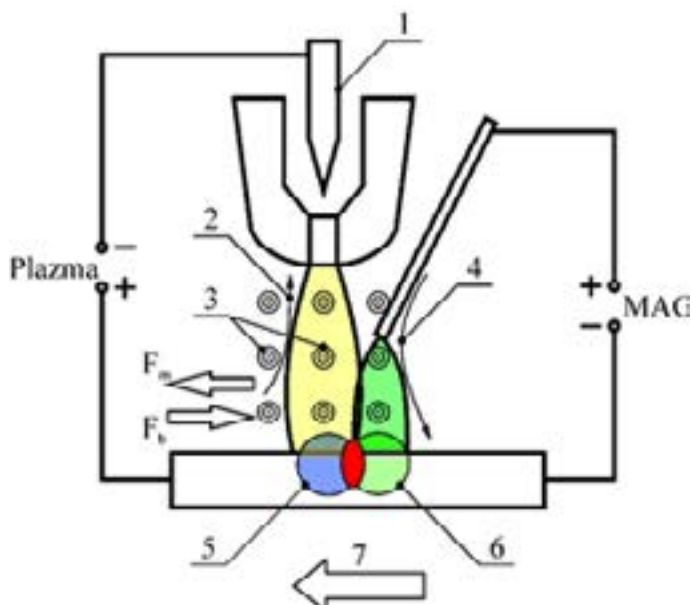

Fig. 5 Schematic HPAW process, where force pushing away plasma arc (Fm) is effectively compensated by the force of the magnetic field (Fb), thus enabling the formation of the common liquid metal pool: 1 – non-consumable electrode; 2 – plasma current; 3 – constant magnetic field; 4 –MAG current; 5 – plasma pool; 6 – MAG pool; 7 – welding direction
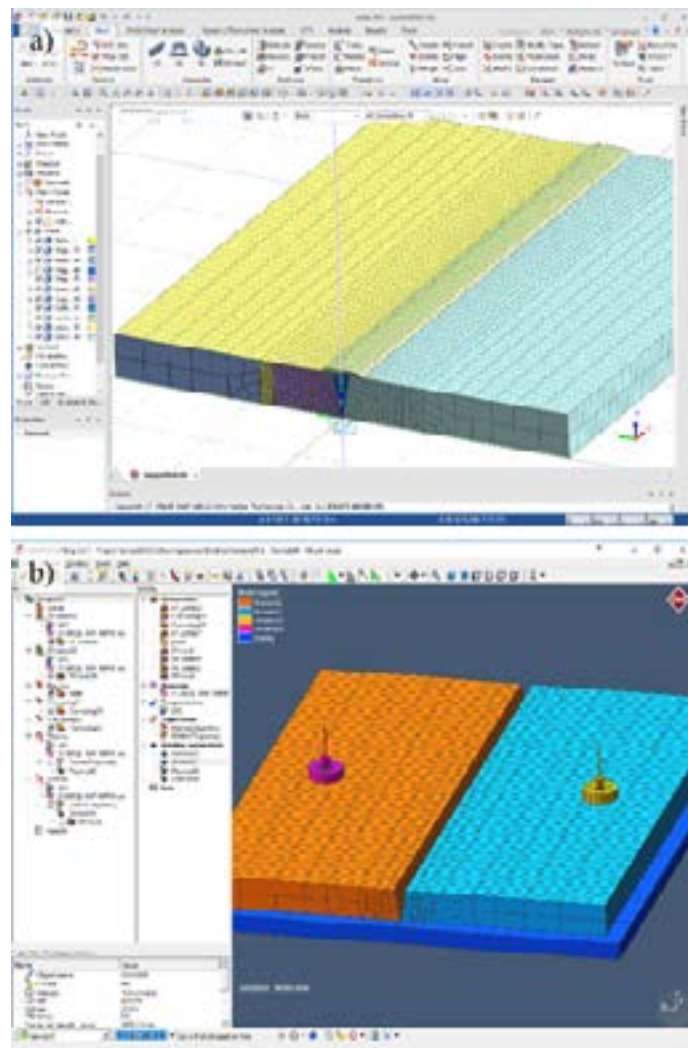

Fig. 6. Modelling of the welded joint subjected to analysis: a) 3D model created in the w Midas NFX programme, containing 3 elements, i.e. two V-bevelled plates and the weld; b) joint model (containing two plates, table and two clamps) imported to the Simufact.Welding programme

universal Nastran Bulk Data File format. The meshes of constituent elements of the joint were imported to the simulation environment, where the remaining joint-related elements, i.e. i.e. the support (welding table) and clamps were generated (Fig. 6). Presently, there are no precise and reliable thermal models allowing for interactions of plasma energy with the classical Goldak model describing the arc process. The implementation of the hybrid welding process in the FEM environment required the development of the numerical model of a complex heat source corresponding to the actual one. In the Simufact.Welding programme, the hybrid heat source was defined as two consecutive processes occurring at a distance corresponding to the head geometry. The two-predefined models of the heat source included the concentrated model related to the plasma process and the bi-ellipsoidal Goldak model for related to MAG process (Fig. 7)

Hybrid welding simulation

The hybrid welding process was simulated using parameters presented in Table 1. At the same time, welding tests were performed using a robotic hybrid welding station. The tests involved 9.5 mm thick V-bevelled plates made of steel S1300QL. The groove angle amounted to 20°, (without a gap). During welding, time t8/5 was measured using a thermocouple sensor immersed in the liquid metal pool. The observation of the penetration process and time t8/5 in the axis of the welded joint revealed the high convergence of simulation results with results of measurements performed during technological tests (Fig. 8).

The convergence was also confirmed in previous tests [5] involving the statistical analysis of the correlation of results related to time t8/5 and experimental data, where the value of Pearson coefficient amounted to 0.99.
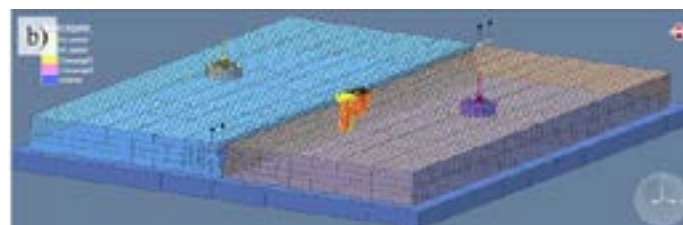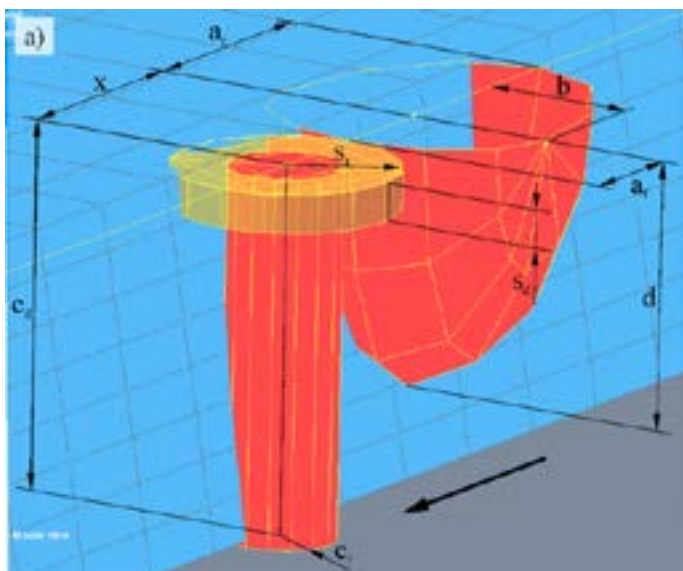
Fig. 7. Numerical model of the HPAW heat source defined in the Simufact.Welding software programme; the model combined the concentrated model and the classical bi-el-lipsoidal model: a) characteristic geometrical parameters of the heat source; b) trajectory of the model in the joint subjected to analysis

As regards the joint subjected to analysis, the difference of time t8/5 across the joint amounted to 1.8 seconds. Because of the limited occurrence of temperature exceeding 800°C, the above-named area did not contain the crucial bright and soft zone (see the metallographic specimen in Figure 8).

Table 1. Parameters used in the simulation of the hybrid welding of steel S1300

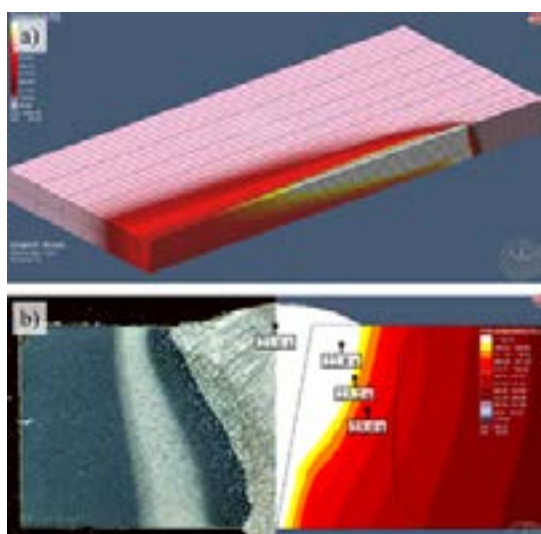| Parameter	Value
Welding rate vsp	100 cm/min
Preheating temperature T_p	180°C
Plasma: current I_p / arc voltage U_p	347 A / 25.2 V
MAG: current I_m / arc voltage U_m	350 A / 31.7 V
Heat input Q	9.5 kJ/cm

Fig. 8. Results of the HPAW process simulation: a) simulation of the hybrid welding on the model specimen; b) comparison of penetration and determined values of t8/5 in the cross-sectional area of the joint

Conclusions

The primary reason for the use of advanced martensitic steels in industry is the problem with the heat balance during conventional welding. The numerical prediction involving the use of verified (material and heat source-related) models enables the adjustment of optimum process parameters.

The test results presented in the article reveal significant differences in values of cooling time t8/5 across the joint. The above-named cooling time value is a key parameter taken into consideration when making decisions related to the performance of preheating or changes in welding parameters. The use of time t8/5 is not possible in relation to the entire heat affected zone, particularly in terms of the crucial tempered area of the soft zone, where temperature does not reach 800°C. In view of the foregoing it should be noted that analytical calculations or measurements of temperature in the weld pool during technological welding tests of martensitic steels are of very limited use. In relation to the issue presented in the article, the Finite Element Method is characterised by very high accuracy and sufficient resolution enabling the identification of any properties at every point of the joint.

The precise definition of a material and that of the heat source enables the continuation of tests concerned with the highly efficient welding of advanced high strength steels. The testing

methodology developed on the basis of the tests performed within the research makes it possible to create numerical thermal models for other improved variants of HPAW power sources and other innovative welding processes.

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