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REMARKS ON THE WELDABILITY PROBLEM OF THE FERRITIC STEELS

ABSTRACT

The thermal – mechanical interactions in welding process of the ferritic steels are described. The definition of numerical analysis of weldability and short discussion on this problem has been presented. Furthermore the actual development of correlations between: thermal field – microstructure and mechanical properties are characterised. It enables to establish the methodology for steels weldability investigation on basis of current calculation standards. Finally, some remarks about possibilities of application of the neural networks methods for estimation of weldability of ferritic steels are presented.

***Key words**: weldability, ferritic steels, mathematical modelling.*

INTRODUCTION

Relationship between microstructure and mechanical properties of structural materials is still relevant problem in the theory of materials science and mechanical engineering. This problem is also important as rational approach towards the design of weldments and welding procedures which can benefit from quantitative and reliable models. The question is how the macro – mechanical parameters can be derived from the microscale mechanisms taking into account local structural heterogeneities. Another question is how to make quantitative descriptions of the strength and toughness properties of welded joints made of non-matching weld metal. These problems are the objects of welding and mechanical investigation and they are related to estimation of weldability. The computational weld mechanics is concerned with the analysis of temperatures, microstructure transformations, strains and stresses in welded structures. The modelling approach to the materials design and processing is important and demanded by industry due to the high costs of empirical experiments. Good modelling techniques can reduce the time from conception to production, can provide quantitative tools of lasting value and permit a reliable and easy route for the transfer of technology between science and industry. Basic science is not yet ready to challenge the necessary problems. Currently the welding as a technological process is treated as a special processes, the results of which cannot be evaluated by the subsequent production control. Numerical weldability analysis is a new powerful research and development tool which is useful for metallurgists, technologist and design engineers. Weldability denotes the possibility to join parts by welding under defined conditions of design, materials and manufacture [1]. Weldability is evaluated conventionally and further developed by testing – empirical approach. This process can be enhanced and made more efficient by mathematical modelling and numerical analysis – theoretical approach. Saying strictly the numerical analysis of a weldability comprises thermodynamic, thermomechanical and microstructural modelling of the welding process. The result of this analysis is material susceptibility for welding process level estimation which physical measure is the fracture resistance. This parameter decides on the suitability of welded joints – Fig. 1.

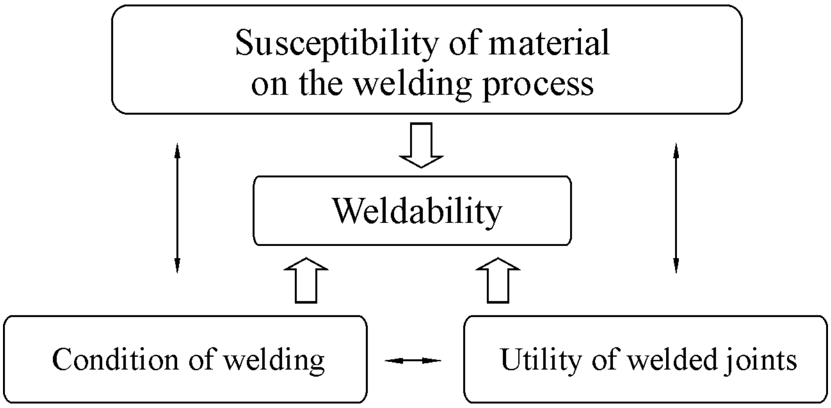

Fig. 1. Coupling between the different fields characterised the weldability in accordance with PN-84/M-69005

THE PHYSICAL MODELLING OF THE WELDING PROCESS AND WELDABILITY OF THE FERRITIC STEELS

The welding process is related with the local change of the internal energy E of welded system and the change of E can be defined by general dependence:

$$E = \sum_{j=1}^{n} \varphi_j \psi_j \tag{1}$$

where:

φ_j - intensive parameters,
ψ_j - extensive parameters.

The intensive parameters are field magnitudes, creating time – space field where in every space point a real physic magnitude is defined.

The extensive parameters may be transported and summed up in finish dimension areas. Some examples of change E in welded joints through interaction of the parameters φ and $\Delta\psi$ are presented in Tab.1.

The selection of the proper intensive parameter φ_j related with the extensive parameter $\Delta\psi_j$ and energy E is possible to perform according to dependence:

$$\varphi_j = \partial E / \partial \psi_j \tag{2}$$

The knowledge of the run of thermo-dynamical process under welding indicates on the possibility of active modelling and control of welding process. Moreover, in calculating process there are material parameters, e.g. thermal conductivity λ, thermal diffusivity α, specific heat c, etc.

***Table 1**. Characteristic of change of the internal energy E as result of interaction of parameters φ and $\Delta\psi$.*

Kind of interaction between φ and $\Delta\psi$	**Change of internal energy E**
thermal	T ΔS [T-temperature (φ), ΔS - entropy ($\Delta\psi$)],
mechanical	p ΔV [p-pressure (φ), ΔV - volume ($\Delta\psi$)],
chemical	$\mu_i \Delta m_i$ [μ_i-chemical potential (φ), Δm_i- mass of i-component ($\Delta\psi$)].

The transport process of the extensive magnitudes requires observations and estimation of the intensive parameters during welding and is realised by using such procedures as transient Lagrangian or steady state Eulerian formulations of thermal cycle.

We can define Eulerian (moving) frame with origin at the centre of the source and co-ordinates (x, y, z). For cartesian co-ordinate system (x_0, y_0, z_0) which remains stationary for all time t and the loading history, the Lagrangian co-ordinate reference is defined.

The definition of theoretical structure of research object is performed with the use of:

- the physic model, describing the actual object,
- the mathematical model, being an equation or system of equations, describing processes together with the boundary conditions, characteristic for given phenomenon.

The mechanical behaviour of welded joints is sensitive to the close coupling between heat transfer, microstructure evolution and mechanical fields. An outline of the couplings between the different fields in the modelling of welding is given in Fig. 2 [2]. Although the effects of microstructure and stress – strain evolution on heat transfer are not large, the effect of temperature on the microstructure and thermal stress is dominant. In addition, the coupling between microstructure and thermal stress can be strong and subtle. The modelling of the fluid flow in weld is not included in Fig. 2, because the effect of the fluid flow on the deformation and stress field is negligible [3].

In the past years considerable progress has been made in developing numerical methods to solve this coupled problem with increasing speed and accuracy. Realistic welds may involve numerous passes, each of which contributes to mechanical and metallurgical effects [3]. There exists an overwhelming number of approaches to and results from empirically and theoretically based mathematical models of weldability, i.e. welding processes, of material behaviour in welding and the strength of welded structures.

The microstructure development in the weld metal region is most complicated. This complication arise because of various physical processes that occur in the arc plasma vapour state, weld metal liquid state and solid state. The result of the each physical process that dominates at higher temperature influences the phase changes at lower temperature. For example, physical processes such as elemental transport in the weld metal, evaporation of alloying elements from the weld metal and gas – metal reactions control the final composition. The weld metal composition, in turn, controls the microstructure development during solidification and solid state transformations. This type of sequential dependency of microstructure development in weld metals exist in almost all alloy systems [3].

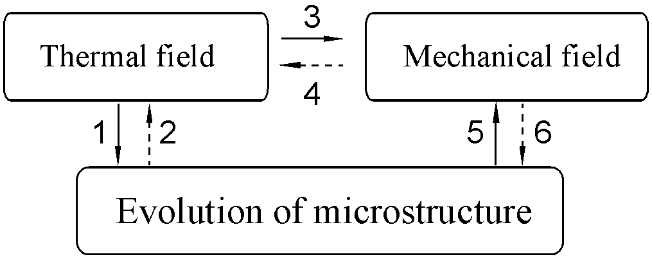

Fig. 2. Coupling between the different modules in welding analysis: 1-microstructure depends on hermal history, 2-thermal history is affected by latent heats and other thermal properties, 3- thermal expansion, 4-mechanically generated heat, 5- mechanical properties depend on microstructure evaluation caused by volume changes due to the phase transformations and transformation–induced plasticity, 6-tranformation kinetics depend on stress.

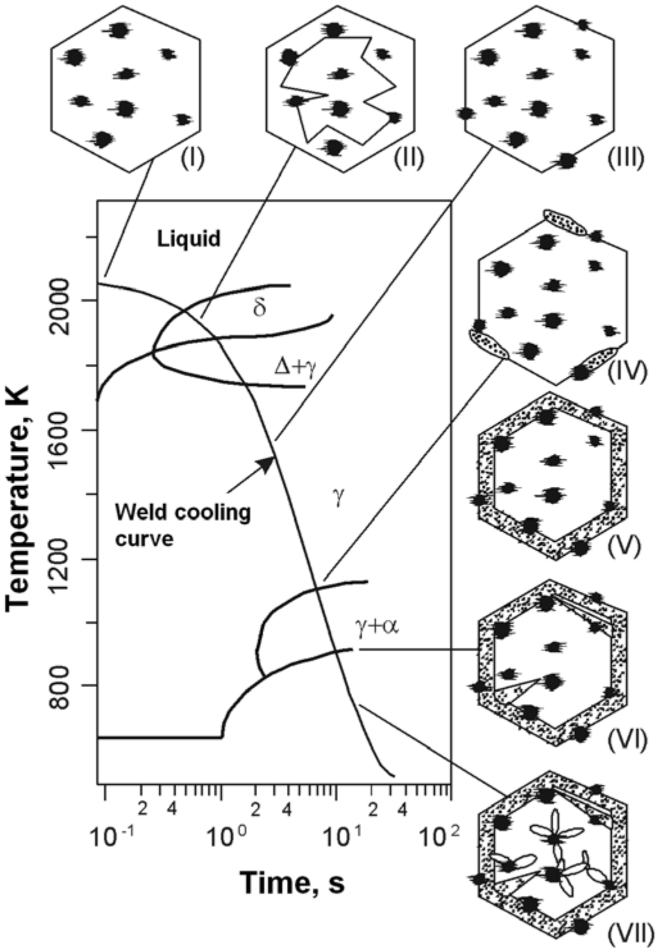

Fig. 3. The diagram of continuous cooling transformation showing the development of weld metal microstructure in low-alloy steels. I-inclusion formation, II-solidification of liquid to δ-ferrite, III-fully austenitic structure, IV-nucleation of allotriomorphic ferrite, V-growth of allotriomorphic ferrite all along the austenite grain boundaries, VI- Widmanstätten ferrite formation, VII-acicular ferrite formation.

An example of this sequential dependency of microstructure development in low-alloy steel weld metal is presented in Fig. 3 [4]. The steel weld pool region is usually heated to temperature as high as 2500 K. As the weld metal cools from above temperature, in the temperature range 2300 to 1800 K, the dissolved oxygen and deoxidising elements in liquid steel react to form complex oxide inclusions of 0,1 to 1 μm size range. The phase transformation from δ ferrite to austenite controls the austenite grain size which, in turn, controls the transformation kinetics of austenite to allotriomorphic ferrite. In the temperature range 1100 – 500 K the austenite transforms to different ferrite morphologies: allotriomorphic ferrite, Widmanstätten ferrite, and acicular ferrite. Furthermore, all of the processes indicate from I – VII are controlled by weld metal composition. As characterised earlier, the ultimate weld metal composition will be decided by the physical processes that occur in the arc plasma. It is practically impossible to model the microstructure development without considering the influence of all the relevant physical processes. Till now, an integrated model that comprises all of the above processes is yet to be developed. The development of such a model depends on the identification of various modelling tools for the fundamental description of various physical processes that occur in welds. Various models tend to solve the fundamental differential equations governing physical processes either by deterministic analytical techniques or numerical methods. In the models describing phase change, thermodynamic descriptions of phases are needed. This data can be obtained from published experiments and used to compute phase diagrams. In addition, tools such as differential thermal analysis and differential scanning calorimetry can be used to evaluate some key parameters such as: heat of fusion, stored strain energy, transformation temperatures needed for modelling microstructure development in welds. The theoretical, numerical and experimental instruments available for the weld microstructure modelling is presented in Fig. 4. According to former configuration we can ascertain that [4, 5]:

- weld solidification controls the size and shape of grains, segregation and defects such as porosity and hot cracks,
- solidification in weld metal region is complicated by several factors:
  - dynamic nature of the welding process,
  - unknown weld pool shape,
  - epitaxial growth,
  - variations in temperature gradient and the weld metal cooling rate may vary from 10^2 to 10^3 °C s^{-1} for the conventional welding process to 10^5 to 10^7 °C s^{-1} for high – energy beam processes,
- solute distribution during weld pool solidification is an important phenomenon resulting in segregation that can significantly affect the weldability, microstructure and properties,
- a lot of attention has been given to modelling the microstructure in weld metal regions and in addition to phase transformations in solid state during weld thermal cycles,
- the transformation of austenite to various ferrite morphologies in low-alloy ferritic steel weld metal is very sensitive to prior austenite grain size and there is a need for models to predict the austenite grain size as a function of weld metal compositions and welding process variables,
- the austenite grain size is assumed to be inversely proportional to the nucleation rate is function of $\Delta G^{\delta\rightarrow\gamma}$ (G- Gibbs energy).

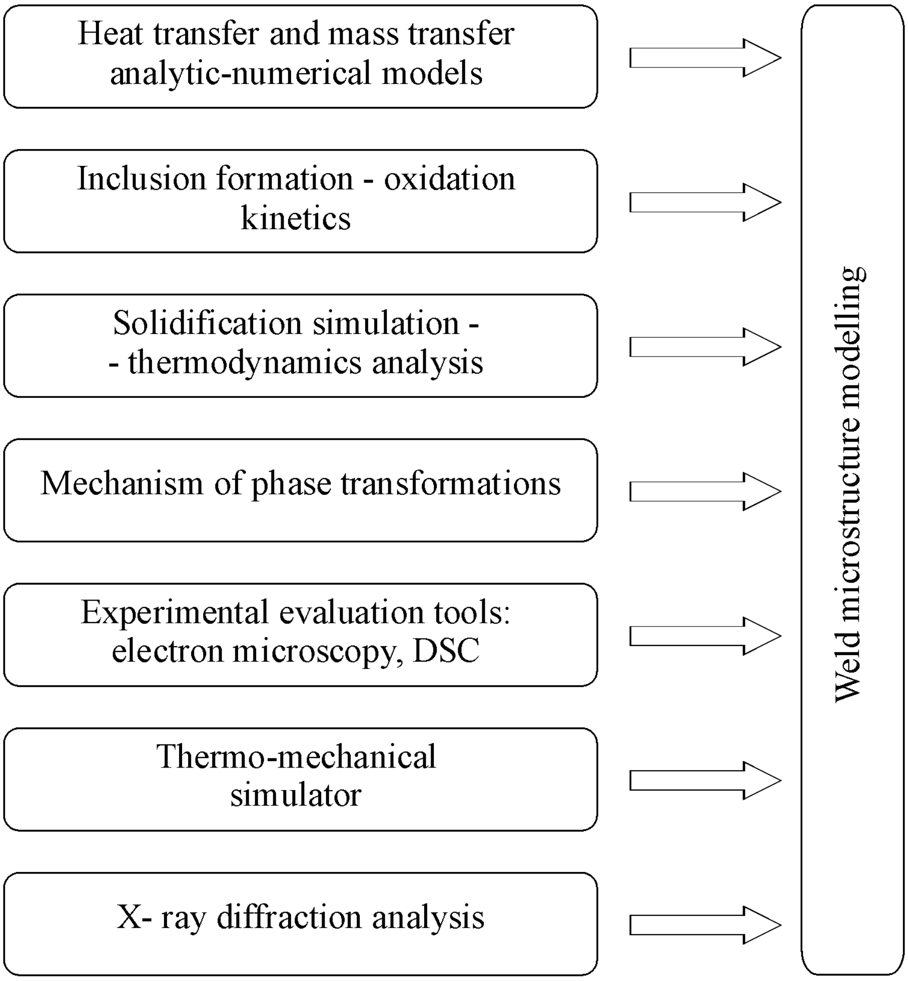

Fig. 4. The survey of theoretical, numerical and experimental tools available for weld microstructure modelling. DSC – differential scanning calorimetry.

NEW DIRECTION OF ESTIMATES OF THE MICROSTRUCTURES AND WELDABILITY OF THE FERRITIC STEELS

Thermodynamic analysis of above kind has undoubtedly been the most successful of all modelling techniques. This analysis is useful particularly because it “links together many variables so that they can be seen to be a consequence of a few” [5]. Elements lose their identity – they simply contribute to an overall free energy – for example Gibbs energy. The friendly output of the such calculations consists of phase fractions and compositions as a function of the overall alloy composition (>20) and variables such as temperature T and pressure (see Tab. 1). Calculated phase diagrams rely on thermodynamics alone-they can deal with equilibrium, metastable equilibrium or equilibrium which are constrained. Most useful microstructure cannot be estimated from phase diagrams because they are not at equilibrium, but the thermodynamic parameters are essential inputs to kinetic theory which describes the approach to equilibrium [6]. If the mechanism of transformation is know, it is possible to apply kinetics theory to model the development of microstructure. The simplest assumption in kinetic theory is to take a "flux" to proportional to a "force". The flux could represent an interface velocity, an electrical current or a heat flux, with the driving force, the electromotive force and temperature gradient representing the corresponding forces. An example for welding is presented in Fig. 5. The experimental determination of the data presented in Fig. 5 would cost in excess of £ 100 000 [6]. It is very important that the physical models described above are capable of predicting entirely new phenomena.

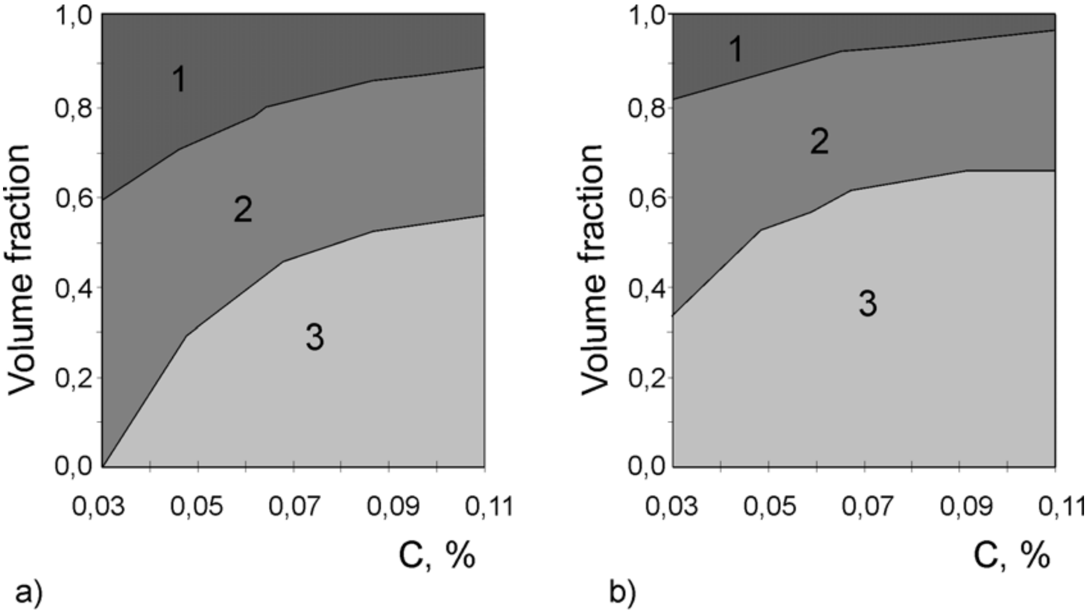

Fig. 5. Calculated microstructure of weld deposits in low alloy C-Mn steel: a. the microstructure of the boron-free alloy, b. boron concentration of 20 ppm. 1- Widmanstätten ferrite, 2- allotriomorphic ferrite, 3- acicular ferrite.

There are difficult problems when the general concepts might be understood but which are not as yet amenable to mathematical treatment. Empiricism can in these circumstances be extremely useful. In this situation the regression analysis, where data are best-fitted to a specified relation-ship is very often used. A more general method of regression is neural network analysis. The transfer from the inputs x_j to the output y is [7]:

$$y = \sum_i w_i^{(2)} \left[\tan h \left(\sum_j w_{ij}^{(1)} x_j + \Theta_i^{(2)} \right) \right] + \Theta^{(2)} \tag{3}$$

Linear functions of the inputs x_j are operated on by a hyperbolic tangent transfer function. The bias is designed Θ_i and is analogous to the constant that appears in linear regression. The strength of the transfer function is in each case determined by the weight w_{ij}. The specification of the network structure: input units – hidden units – output unit, together with the set of weights is a complete description of the formula relating from the inputs to the output. The weights are determined by training the network [6, 7]. The complexity of the model is controlled by the number of hidden units. Presently, neural networks are clearly extremely useful in recognising patterns in complex data and the methodology is used extensively in process design and alloy design.

CONCLUSION

A definition for numerical analysis of the weldability is given and the new aspects of the weldability assessment is presented. The paper explains the sequential dependency of each of the physical processes in the welding situation.

The importance of the fundamental understanding of mechanisms of physical processes in welded joints and the validation of models with advanced experimental tools is also emphasised.

In the work indicate too that the neural networks are useful in complex data such as the weldability assessment.

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