APPLICATION OF ANALYTICAL METHODS FOR THE MODELING OF HEAT AFFECTED ZONE OF WELDED JOINTS

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Abstract

In the paper the method of predicting the structural composition and mechanical properties of heat affected zone (HAZ) welded joints using the analytical methods was presented. On the basis of presented phenomenological formulas the computational CCT diagram and corresponding with it phase composition according to cooling rates of S355 steel was created. These values were used to predict the structural composition and mechanical properties of HAZ welded joint. The mechanical properties of HAZ through arising structure in this area and mechanical properties of individual phase components were determined. The predicting of phase composition and mechanical properties of the HAZ was performed for the front of the weld joint carried out with the laser technology. The ABAQUS FEA engineering software was used in order to determine the temperature field. In the calculations, the mathematical model of the volume source welding, based on the distribution of power described by Goldak distribution was applied. On the basis of the temperature distributions in the welded joint, the phase composition and mechanical properties of the HAZ were determined. For the purpose of verification of the results, the experimental studies of the base material investigated steel were performed.

Keywords: Phase transformations, phase volumetric fraction, heat affected zone, analytical methods, mechanical properties

1. INTRODUCTION

Due to variable temperature field, welded material during the welding process changes its physical and mechanical properties. The largest changes the material properties are present in heat affected zone (HAZ), where as a result of phase transformations occurred various structures conditioned by thermal cycle. Mechanical properties of HAZ of welded joint are determined by the structure of the welding join. Therefore it is important from the point of view of the formal rules of modelling mechanical phenomena predicting numerical phase composition. Existing methods can be classified into numerical, using mathematical models and experimental CCT diagrams and analytical models [1, 2]. The analytical models for CCT diagrams construction, the determination of the phase composition and mechanical properties was based on the chemical composition of the steel [1, 2, 4].

The paper presents the numerical predicting the phase composition and mechanical properties of laser welded joint using analytical methods. Analytically determined CCT diagram and the corresponding diagram of microstructures as a function of time $t_{8/5}$ and identified the mechanical properties of a particular type of steel: hardness (HV) impact strength (KCU), yield point (R_e), tensile strength (R_m), elongation (A) and the constriction (Z). On the basis of determined volume was performed numerical predicting phase composition and mechanical properties for flat steel of high strength, butt-welded laser technology. To determine the temperature field program Abaqus FEA was used. In the application Abaqus FEA constructed three-dimensional discrete model reflecting the geometry of the considered configuration. On the basis of the appointed temperature field, determine the shape and size of the zone melting of the welded joint and determined mechanical properties of welded joint.

2. EXPERIMENTAL STUDIES OF MECHANICAL PROPERTIES OF S355 STEEL

Experimental studies of the base material S355 performed at the Laboratory Strength of Materials Institute of Mechanics and Machine Design at the Technical University in Czestochowa. Tensile test specimens of S355 were performed on a testing on the machine Z100 Zwick/Roell. Five samples were made by standards - DIN EN 10002-1: 2001. Hardness test samples from S355 performed on a stationary universal hardness equipment INNOVATEST. The results of the experimental tests were shown in **Table 1.**

Table 1 Mechanical properties of S355 steel

HV [-]	Re [MPa]	R_M [MPa]	A[%]	Z[%]
168.2	358	565	13.4	38

3. ANALYTICAL AND EXPERIMENTAL CCT DIAGRAMS AND PHASE VOLUME FRACTIONS

Analytical models created on the basis of the chemical composition of steel are used to predict the structure composition of HAZ, further to develop simplified CCT diagrams Equations are obtained by the use of statistical analysis of results of experimental research performed for certain material groups. These relationships concern the start and finish temperatures and times of phase transformations during heating and cooling [1, 2 3]. Analysis of phase transformations presented in this paper refer to a group of weld-able low carbon and high strength steels, including analyzed S355 steel. Chemical composition of steel S355 **Table 2** shows.

Table 2 Chemical composition of S355 steel (wt. %)

Steel	C	Mn	Si	P	S	Al	Cr	Ni
S355	0.19	1.05	0.20	0.028	0.02	0.006	0.08	0.11

In this paper were used analytically determined CCT diagram and phase fraction of individual structures analysed steel. Determining simplified CCT diagram and phase fraction for analytical methods were shown in [1, 3, 5].

In welding processes high-speed heat source of high-power significant effect on the kinetics of phase transformations, in addition to a heating and cooling rate has a maximum temperature of heating. During the reducing the austenitization temperature identified maximum temperature of temperature cycle, start and final times of transformation ($t_{8/5}$) move in the direction of the shorter cooling times. As a result, the CCT diagrams to the various heating temperatures for the same cooling time ($t_{8/5}$) are obtained various structures. These relationships can be described by maximum Temperature- Cooling- Time diagram of kinetics transformation as a function of the maximum temperature of the thermal cycle of welding [5]. This diagram obtained experimentally, however, is very expensive and laborious. Good results are also obtained by using linear movement of the CCT diagrams as a function of the maximum heating temperature (temperature of austenitization) described in [5]. In this model, it is assumed that the axial movement of the two diagrams relative to each other is proportional to the austenitization temperature difference corresponding to these diagrams.

$$t_i(T_{Max})_{M,,FP,B} = \frac{(T_{Max}^{T_i} - T_p(t_j))t_j}{T_{Max}^{Tj} - T_p(t_j)} \tag{1}$$

where: T_{Max}^{Tj} is a starting temperature of austenitization, T_{Max}^{Ti} is a new temperature of austenitization, T_p is the temperature of the start of phase transformations, whereas t_j is start time of this transformation.

In this paper used this model in the analysis of phase transformations. Dilatometric research on high strength steel was carried out in order to verify obtained analytical results and to evaluate the usefulness of created diagram of austenite transformation. Dílatometric research was performed the DIL805 Bahr Thermo-analysis GmbH dilatometer. The temperature of austenitization T_A=1200 °C and heating rate 100 K / s were assumed in dilatometric research as well as different cooling rates simulating thermal cycles in welding. The analytical models were created on the assumption an austenitization temperature of 1300 °C [2, 4]. For comparison CCT diagrams, analytical diagram was transferred according to (1). CCT diagram comparison and phase volume fraction of individual structures obtained by the analytical methods and using experimental studies were presented in **Figure 1.**

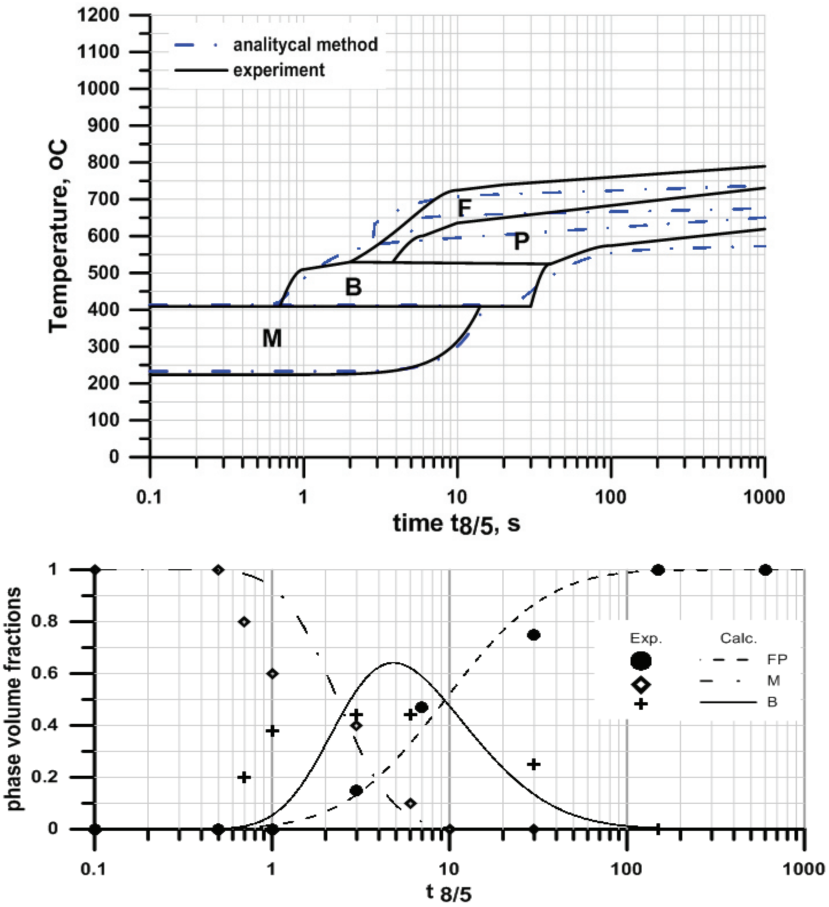

Figure 1 CCT diagram [3] of S355 steel and phase volume fractions

4. ANALYTICAL MODELS TO PREDICT MECHANICAL PROPERTIES IN WELDED JOINTS

Mechanical properties of HAZ can be determined from the structural composition and mechanical properties of each structure. If the phase composition in the heat affected zone is known, more specifically contribution of each structure (ferrite-pearlite, martensite and bainite) and properties of structural components W_i, there is a possibility to approximately predict properties of the entire zone [7].

$$W = \sum_{i=M,B,F,P} W_i \eta_i \tag{2}$$

Where: W_i can be hardness, yield point, tensile strength, elongation and necking, η_i is contribution of individual structural components.

Many dependencies are discussed in the literature [2, 5], which can determine mechanical properties such as: R_e, R_m, A_5, Z, and HV. Property of each phase: ferrite-pearlite, martensite and bainite are defined on the base of chemical composition. Symbols of chemical elements provided by all empirical formulas represent percentage of a given element, e.g. C→%C.

Hardness, yield points and tensile strength of each phase: ferrite-pearlite, martensite and bainite can be determined with a high probability by Kasatin and Seyffart equations [2]. These equations (eqs. 3-5) are determined by steel chemical composition:

Hardness:

$$\begin{aligned} HV_{FP} &= 98 + 275C - 15.4Mn \\ HV_{M} &= 309 - 494C + 622C^2 + 17.7Mn \\ HV_{B} &= 234 + 122C \end{aligned} \tag{3}$$

Yield points:

$$\begin{aligned} Re_{FP} &= 187 + 92C + 47Mn + 90V \\ Re_{M} &= 602 + 2150C + 500Mo \\ Re_{B} &= 500 + 460C - 120C^2 + 150V + 360Mo \end{aligned} \tag{4}$$

Tensile strength:

$$\begin{aligned} Rm_{FP} &= 297 + 1360C + 60Mn + 140V \\ Rm_{M} &= 798 + 3215C \\ Rm_{B} &= 590 + 960C + 39.7Mn + 200V \end{aligned} \tag{5}$$

Elongation (A_i) and necking (Z_i) for structure components can be defined by (eqs. 6 and 7) as a function of steel chemical composition and time t, where t is the cooling time between temperatures 800 °C and 500 °C.

Elongation:

$$\begin{aligned} A_{M} &= 12.267C^2 - 1.5Mn + 0.76\ln t \\ A_{B} &= 21.3 - 35.6C - 4.0Mn - 5.0V + 1.84\ln t \\ A_{FP} &= 36.5 - 127C + 153C^2 - 1.16Mn + 8.0V + 0.66\ln t \end{aligned} \tag{6}$$

Necking:

$$\begin{aligned} Z_{M} &= 48.5 - 158C + 116C^2 - 0.98\ln t \\ Z_{B} &= 53.3 - 132C + 103C^2 - 5.1Mn - 10V + 3.4\ln t \\ Z_{FP} &= 65.4 - 88C - 82C^2 - 6.7Mn + 18V + 0.6\ln t \end{aligned} \tag{7}$$

5. EXAMPLES OF CALCULATIONS

In paper to analysis butt-welding of S355 steel sheets of dimensions 150 x 30x3 mm is assumed. Modelling of movable welding source is implemented in ABAQUS FEA [7] using additional numerical DFLUX subroutine. Double elliptic surface laser heating mathematical model of welding source (depth source z=0) of Goldak heat source power distribution is used in calculation [8]. Equation of temperature field is completed by initial and boundary condition of Dirichlet, Neumann and Newton type with heat loss through the convection and radiation [9]. In calculation temperature field is used power of the arc Q = 2200 [W] and welding velocity v = 9 [mm / s].

Numerical calculations of the temperature field are performed as 3D task. Cross section of considered welded joint and temperature distribution at different distance from the centre of the heat source was presented in

Figure 2, where analysed material points were marked. On the basis of determined temperature distributions the analysis of phase transformations is performed.

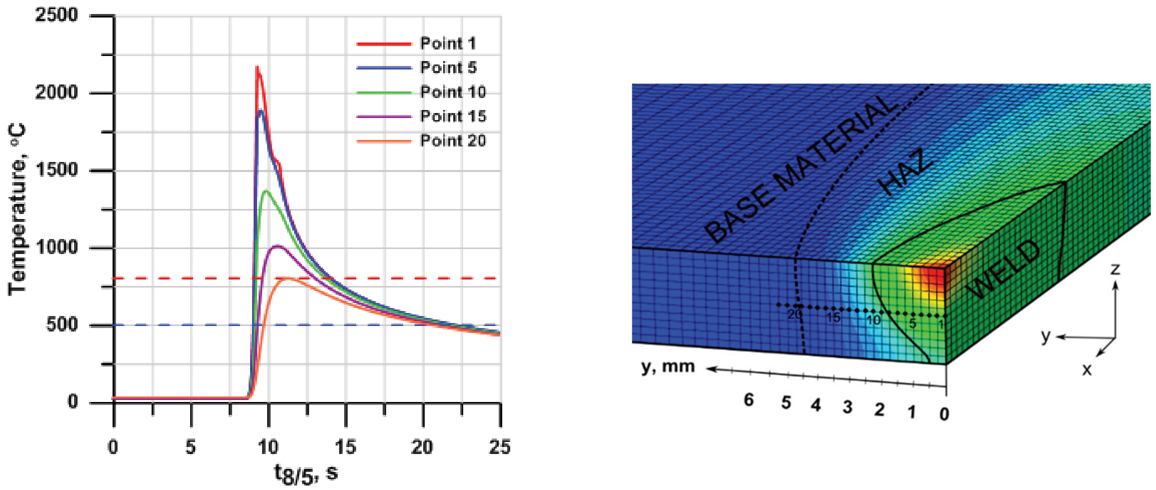

Figure 2 Cross section of considered welded joint and temperature distributions at different distances from the centre of the heat source

Prediction of mechanical properties in the weld and HAZ are performed using relationships (eqs. 3-7) and analytically defined volume fractions. Distributions of mechanical properties as a function of time $t_{8/5}$ determined by (2) in the cross-section of welded joint. Respectively distributions of hardness (HV), yield point (Re), tensile strength (R_m), elongation (A) and necking (Z) are presented in **Figure 3**. Areas of occurrence of weld, HAZ and base material investigated steel, as well as the experimentally obtained mechanical properties of the base material were marked on each of the graphs.

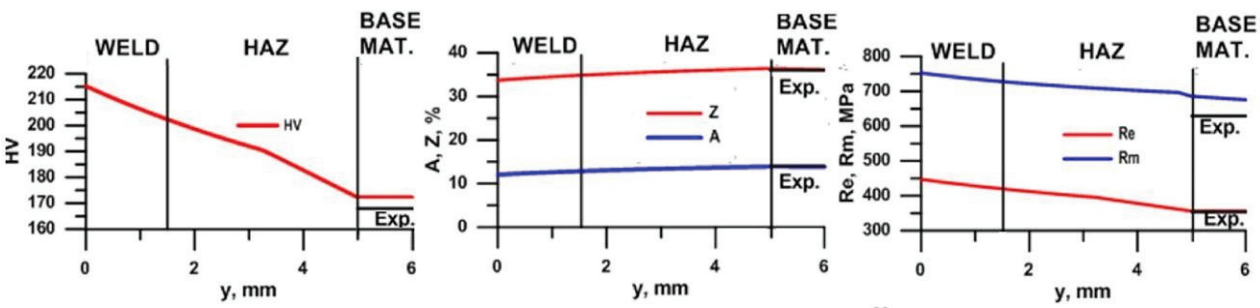

Figure 3 Mechanical properties of welded joint

6. CONCLUSION

Analytical methods to create simplified CCT diagrams and predicting HAZ structure based on the chemical composition of the steel are very useful and inexpensive tool for assessing the microstructure of the joint, and consequently the mechanical properties of the weld joint. In this paper, the usefulness of CCT diagrams and formed microstructure and consequently mechanical properties in HAZ of welded joint have been assessed.

To determine the mechanical properties of welded joints were used analytically determined phase fractions of ferrite-pearlite, bainite and martensite and the mechanical properties of individual structures. Determined mechanical properties of the material in the weld and HAZ are the result of used welding technology, temperature distribution in the material and phase transformations investigated steel.

Determined by the analytical analysis, the mechanical properties of welded joint are confirmed by experimental results. Mechanical properties obtained using analytical methods can be applied for the preliminary analysis of material properties intended for different welded constructions. They can also be used as input data in numerical analysis of stresses and deformations in welded elements, substituting expensive experimental research in this field.

REFERENCES

[1] MIKUŁA, J. Analityczne metody oceny spawalności stali, Zeszyty naukowe, Mechanika, 2001, vol. 85, pp. 53-57.

[2] SEYFFARTH P., KASATKIN O. G., Mathematisch-statistische Beschreibung der Austenitumwandlung in der Wärmeeinflußzone. Schweißtechnik, 1979, vol. 29, pp. 117-119.

[3] PIEKARSKA W., GOSZCZYŃSKA D., SATERNUS Z., Application of analytical methods for predicting the structures of steel phase transformation in welded joints. J. Appl. Math. Comput. Mech, 2015, vol. 14, pp. 61-72.

[4] KASATKIN O. G., SEYFFART P., Interpolâcionnye modeli dlâ ocenki fazovogo sostava zony termičeskogo vliâniâ pri dugovoj svarke nizkolegirovannyh stalej. Avtomat. Svarka, 1984, vol. 1, pp. 7-11.

[5] PIEKARSKA W., Modeling and analysis of phase transformations and stresses in laser welding process , Archives of Metallurgy and Materials, 60 (4), s. 2827-2835, 2015

[6] SHEN H., SHI Y., YAO Z., HU J., An analytical model for estimating deformation in laser forming, Computational Materials Science, 2006, 37, 593-598.

[7] SIMULIA Dassault System, Abaqus theory manual, Version 6.7, 2007.

[8] GOLDAK J. A., Computational Welding Mechanics, Springer NY 2005.

[9] DOMAŃSKI T., BOKOTA, A., The numerical model prediction of phase components and stresses distributions in hardened tool steel for cold work, International Journal of Mechanical Sciences, 96-97, 47-57, 2015.