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Z. ŚLODERBACH*,#, J. PAJĄK*

DETERMINATION OF RANGES OF COMPONENTS OF HEAT AFFECTED ZONE INCLUDING CHANGES OF STRUCTURE

OKREŚLENIE ZAKRESÓW SKŁADOWYCH STREFY WPŁYWU CIEPŁA UWZGLĘDNIAJĄC ZMIANY STRUKTURY

A simplified analytical method to determine the range of the heat affected zone and its components during welding is presented. Heat affected zone (HAZ) is an area formed during welding in which, as the result of temperature, some structural changes in the welded material occured. Knowledge of the area and sub-areas of HAZ is important from practical point of view, since the area of the fine-grained HAZ is a critical place in terms of creep strength and thermal fatigue. Heat affected zone is often the cause of future damage of many devices in which welding technology was used for their repair.

Keywords: welding, heat affected zone, weld, length of components of HAZ, pipelines.

Przedstawiono uproszczoną analityczną metodę służącą do określenia zakresu wpływu strefy ciepła i zakresów jej stref składowych podczas spawania. Obszar (strefa) wpływu ciepła (HAZ) to obszar, w którym podczas procesu spawania w wyniku działania wysokiej temperatury zaszły strukturalne zmiany w spawanym materiale. Wiedza na temat obszaru i pod-obszarów HAZ jest ważna z praktycznego punktu widzenia, ponieważ np. strefa drobno-ziarnistego HAZ jest krytycznym obszarem wytrzymałości na pełzanie oraz zmęczenia cieplnego. HAZ (strefa wpływu ciepła) jest często miejscem i przyczyną późniejszego uszkodzenia wielu urządzeń, które naprawiano techniką spawania.

1. Introduction

Heat affected zone (HAZ) - formed during welding is an area in which some structural changes in the welded material take place as the result of experienced temperature. The knowledge of a whole area and of subareas of the HAZ is important from practical point of view, since, as shown in [1], fine-grained HAZ is in a critical place in terms of creep strength and thermal fatigue. This applies in particular to those technological operations, in which welding technologies are used for manufacturing or repair. The HAZ adjacent to the native material intact by heat has a lower creep resistance than the native material and only at maximum load (immediate tensile strength) appears trans – crystalline breakthrough in the native material, as shown in [1]. The cracking of the material beyond the HAZ indicates good ultimate strength of joint, but does not guarantee a good creep strength. In the case of creep, the most dangerous place in the welded joint is (as mentioned earlier) the area of fine-grained structure lying in the heat affected zone.

The structure of HAZ created as a result of welding affects [2]:

- tendency of joint to the formation of cold cracks,
- performance properties of welded construction and in particular its resistance to brittle cracking.

In addition, in materials that previously worked in conditions of high temperature creep, the HAZ decides on mechanical properties around the weld joint.

Calculations of pipelines are based, among others, on the time of operation and according to current regulations the period of 100 thousand working hours, i.e. approximately 13 years of operation time for the pipeline is assumed [3], but straight sections of pipelines can operate reliably at least 200 thousand hours [1]. Other pipeline components such as elbows, tees and joints in the knees and fittings are characterized with much shorter working time. Examples of operational stability of some elements of the pipeline are as follows: T-pipe and Y- pipe branches can work about 150 thousand hours, knees approximately 180 thousand hours and welds connecting straight sections of piping can work about 140-170 thousand hours, see [1, 4, 5]. The calculated times are shorter and respectively for the knees approximately 140 thousand hours and for the welds around 70 thousand hours, see [5] and the corresponding times of special surveillance are even shorter, for example, for the knees 80 thousand hours [6]. Presently, these values are gradually increased based on modern methods of calculations of service life under conditions of mechanical stress and thermo-mechanical properties [7].

In [8] six broad classes of mechanisms of damage of

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* OPOLE UNIVERSITY OF TECHNOLOGY, FACULTY OF APPLICATIONS OF CHEMISTRY AND MECHANICS, LUBOSZYCKA 7, 45-036 OPOLE, POLAND

Corresponding author: z.sloderbach@po.opole.pl

energy pipelines were distinguished, which include basic mechanisms of damages that may independently or in combination cause the damage of pipe walls. The technology of manufacturing or repair of the pipeline should be examined in terms of these six classes of mechanisms of defects, which are the criterion of pipeline durability. One of the most difficult parts of this analysis is to estimate the impact of changes in the structure of material occurring in the HAZ caused by the welding process.

In [9] the authors found that improperly performed heat treatment of the welded joint leads to a crack or damage the load, detected before operation of the pipeline. These damages are inter-crystal cracks and extend generally in the area of coarse-grained HAZ.

Obtaining of welded joint with high-temperature creep resistance similar to the high-temperature creep resistance of native (input) material depends upon the following basic technological factors [9]

- the chemical composition of the binder,
- thermal conditions of welding,
- the stiffness of the welded elements as a whole,
- proper heat treatment after welding,
- the choice of the method and type of welding.

The effect of repeated thermal cycles of welding on the plastic properties and the HAZ structure of 13HMF steel after the working time longer than 130,000 hours and microscopic analysis of the impact of multiple thermal cycles of welding on breaking work and hardness after simulated thermal cycles for different areas of the HAZ (in particular for coarse grain HAZ) for 13HMF steel and P91 steel were recently presented in [10, 11]. These studies can be very useful to analyze the durability (immediate, fatigue and creep) of elements of power equipment working at various temperature. The size of HAZ and its constituent areas is affected by the following factors: material welded, type of welding (arc, acetylene - oxygen, electro-slag, plasma, laser and other), welding time, maximum temperature, value of linear electric energy of welding arc, welding conditions, cooling efficiency, heat exchange and the others. In [1] the authors found, that in case of arc welding of steel the HAZ extends only to a few millimeters, but with oxy-acetylene and electro-slag welding can be much larger.

Therefore, analytical attempt to estimate the extent of HAZ and its constituent areas should help determine with fairly good accuracy the size and extent of occurrence without the need for many costly and time-consuming metallographic studies and hardness measurements.

Additionally, the simplicity of the method (allowing to make calculations using a calculator) and versatility of received expressions (in comparison to the numerical calculations MES performed with a computer) enables the use of this method on the object under field conditions without the use of special software and hardware.

Heat Affected Zone of welded joint is not homogenous, but different sub-zones can be distinguished, see [10, 11]. The distribution of the HAZ of the welded joint of low carbon steel (or low-alloy steel) is shown in Figure 1.

These sub- zones are frequently described by abbreviations shown in Figure 2, taken from [10].

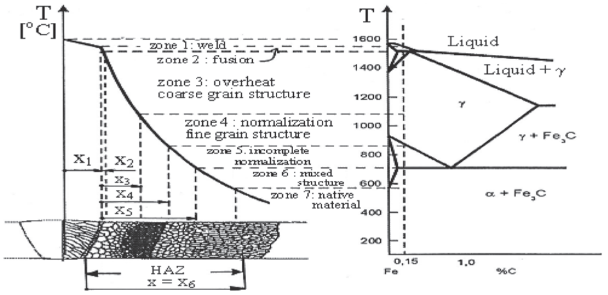

Fig. 1. The example of HAZ structure for carbon steel containing 0.15% C, see [1]

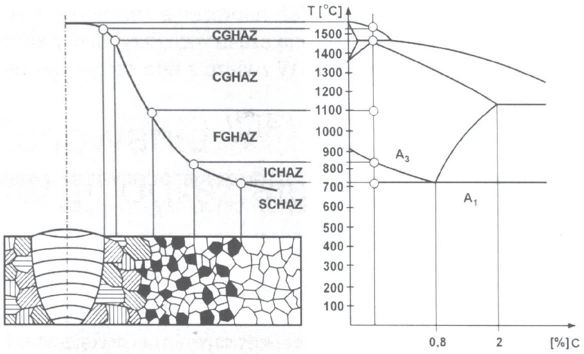

Fig. 2. Distribution of structural areas of HAZ for low alloy steel as a function of temperature, in relation to the iron-carbon phase equilibrium [10]

From comparison of Figures 1 and 2 the following designations could be described:

CGHAZ - zone 2 and 3 (Coarse Grain HAZ) – HAZ with coarse grain structure, heated to temperature (1100°C $\leq T_{max} \leq T_m$), where: T_m – steel melting point,

FGHAZ - zone 4 (Fine Grain HAZ) – HAZ with fine grain structure, heated to temperature above A_3 ($900 \leq T_{max.} \leq 1100$°C),

ICHAZ - zone 5 (Intercritical HAZ) – HAZ heated to temperature above A_1 in the range A_1–A_3 ($700 \leq T_{max.} \leq 900$°C),

SCHAZ - zone 6 (Subcritical HAZ) – HAZ heated to temperature below A_1 in the range ($600 \leq T_{max.} \leq 700$°C).

For carbon steel of carbon content < 0.8% in temperature below A_1 none structural change occur in welded material, see Fig.1. Austenitic change ($\alpha \rightarrow \gamma$) occurs at A_1 temperature. Above A_3 homogenization of austenite occurs. In the temperature range A1 to A3 the growth of austenite grains occurs. For steels with a carbon content of ≥ 0.8% points A1 and A3 overlap. Steel containing 0.8% C is called an eutectoid. High temperatures occurring during the welding process promote austenitization and growth of austenite grains. Contrary, high heating rate and short holding time at high temperature limit the growth of grains.

2. Basic assumptions and relations

The nature of the proposed model includes the analysis of temperature distribution in the half-space, which on the surface $x = 0$ (Fig. 3) is evenly heated in time t with constant maximum temperature $T_0 = T_{max.} = \text{const}$ and the melting point of the binder $T_0 > 0^{\circ}$C. As a result of the assumption of uniform heating of the face space, ($x = 0$), of half-space considered, the temperature T inside material depends only on x and t and does not depend on y and z. Then we obtain that $T = T(x, t)$. With these assumptions, the distribution of temperature change at depth of x is similar to the case of Jomini's long rod, see [12, 13], heated on face surface and isolated on lateral surfaces. Then the temperature distribution in the rod also depends only on the coordinate of depth x and on time t.

Assumptions: $T(x, t)|_{x=0} = T_0 = \text{const.}$ and ($T_0 > 0^{\circ}$C) and $T(x, t)|_{t=0} = 0^{\circ}$C.

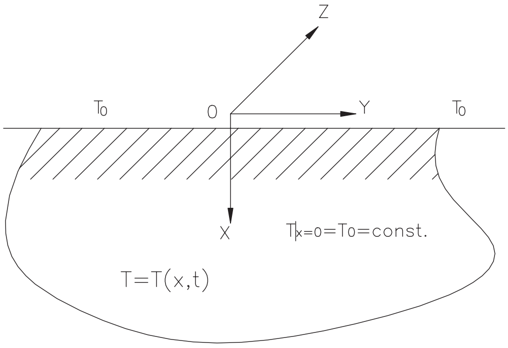

Fig. 3. Scheme of half-space heated to temperature T_0 during time t.

To analyze the problem, one-dimensional equation of heat conduction [13] is used, which is as follows:

$$\frac{\partial T(x,t)}{\partial t} = \kappa \frac{\partial^2 T(x,t)}{\partial x^2} \tag{1}$$

where : T - the temperature inside the welded material in $^{\circ}$C or K,

κ – heat diffusivity coefficient in $\left[\frac{\text{m}^2}{\text{s}}\right]$

t – time of exposure of head surface in seconds on temperature T_0.

Between the heat diffusivity coefficient κ and thermal conductivity coefficient k the following relation takes place

$$K = \kappa \cdot \rho \cdot c, \tag{2}$$

where k - thermal conductivity coefficient in $\left[\frac{\text{J}}{\text{m} \cdot \text{s} \cdot \text{K}}\right]$,

ρ - density of material in $\left[\frac{\text{kg}}{\text{m}^3}\right]$,

c - specific heat in $\left[\frac{\text{J}}{\text{kg} \cdot \text{K}}\right]$.

Solving equation (1) one does not take into account the thermal resistance of the thin surface layer that is formed between the adhesive and the material welded. Then solving Eq. (1), we obtain

$$T(x, t) = T_0\, erf\left(\frac{x}{2\sqrt{\kappa \cdot t}}\right) = T_0\left(1 - erfc\frac{x}{2\sqrt{\kappa \cdot t}}\right), \tag{3}$$

where: $erf\,\tilde{x}$ is a function of error and $erfc\,\tilde{x} = \left(1 - erf\,\tilde{x}\right)$ is so-called complementary error function [13, 14]. These functions are read from the mathematical tables or are calculated using a suitable computer program such as MathCAD

and $$\tilde{x} = \frac{x}{2\sqrt{\kappa \cdot t}} \tag{4}$$

where: $\tilde{x}$ - is a dimensionless parameter that is useful in carrying out the calculations.

After transforming equation (3) can be written in the following form

$$\frac{T(x,t)}{T_0} = erf\frac{x}{2\sqrt{\kappa \cdot t}}\,. \tag{5}$$

This equation will be useful to determine not only the total range of the heat affected zone, but also the extent of the areas and the size of the component areas (sub-areas) making HAZ. Effective and practical application of the above equation will be successively presented in the following examples. Assuming, according to remarks in [1,] that in the HAZ structural changes occur, then according to Fig. 1 it can be assumed, that in order to prevent such changes $T(x, t) \approx 600^{\circ}$C. When the melting point of the binder $T_0 \approx 1550^{\circ}$C then from tables, see [13, 14] we obtain, that

$$erf\frac{x}{2\sqrt{\kappa \cdot t}} \approx 0.3871, \tag{6}$$

and then we receive

$$\frac{x}{2\sqrt{\kappa \cdot t}} \approx 0.61. \tag{7}$$

This expression will be useful in determining the value of x of HAZ for a given time t of action of the temperature T_0 on the forehead area (face of contact of binder with welded material) and knowing diffusivity coefficient κ of given material. Determination and selection of the time t, for a given type and method of welding requires experience, knowledge, expertise, and should be particularly carefully and precisely defined by experts. As can be seen from formula (7), the value of x for a given κ - depends only on the value of time t.

Diffusivity coefficient κ for steel, cast steel and cast iron, $\kappa \cong 0.12 \times 10^{-4} m^2/s$ [13] and x_1, in adopted convention and according to Fig. 1, is half the width of the weld.

3. The calculation of the length of HAZ components

3.1. The total area of heat affected zone

When the melting point of the binder T_0 is about $T_0 \approx 1550^{\circ}$C, then total length x of HAZ based on equation (7) is

$$x \approx 1.22\sqrt{\kappa \cdot t}\,. \tag{8}$$

3.2. Area of fusion penetration

For this area, according to Fig. 1, $T(x, t) \approx 1480^{o}$C and from tables [13] we can read that

$$erf\,\frac{x_2}{2\sqrt{\kappa\cdot t}} \approx 0.955 \text{ and } \frac{x_2}{2\sqrt{\kappa\cdot t}} \approx 0.495, \text{ and then we obtain}$$

$$x_2 \approx 0.1\sqrt{\kappa\cdot t}\,. \tag{9}$$

3.3. Area of overheating

For this area, according to Fig. 1we obtain that $T(x, t) \approx 1100^{o}$C and the values determined from [13] are: erf

$$\frac{x_3}{2\sqrt{\kappa\cdot t}} \approx 0.71 \text{ and } \frac{x_3}{2\sqrt{\kappa\cdot t}} \approx 0.255,$$

and then

$$x_3 \approx 0.51\sqrt{\kappa\cdot t}\,. \tag{10}$$

Hence the length of overheated area (coarse grain structure) is

$$x_3 - x_2 \approx 0.41\sqrt{k\cdot t}\,. \tag{11}$$

3.4. Area of normalization

For this area, according to Fig. 1we obtain that $T(x, t) \approx 850^{o}$C and from tables [13] we obtain the following:

$$erf\,\frac{x_4}{2\sqrt{\kappa\cdot t}} \approx 0.548 \text{ and } \frac{x_4}{2\sqrt{\kappa\cdot t}} \approx 0.417, \text{ so}$$

$$x_4 \approx 0.834\sqrt{\kappa\cdot t}\,. \tag{12}$$

The length of normalization area (fine grain structure) is

$$x_4 - x_3 \approx 0.324\sqrt{\kappa\cdot t}\,. \tag{13}$$

3.5. Area of incomplete normalizotion

For this area, according to Fig. 1, $T(x, t) \approx 720^{o}$C, so from tables [13] we can read that:

$$erf\,\frac{x_5}{2\sqrt{\kappa\cdot t}} \approx 0.465\text{and } \frac{x_5}{2\sqrt{\kappa\cdot t}} \approx 0.567, \text{ hence we obtain}$$

$$x_5 \approx 1.13\sqrt{\kappa\cdot t}\,. \tag{14}$$

The length of incomplete normalization area is

$$x_5 - x_4 \approx 0.296.\sqrt{\kappa\cdot t}\,. \tag{15}$$

3.6. Area of mixed structure

For this area, according to Fig. 1, $T(x, t) \approx 600^{o}$C and it is also the whole range of heat affected zone $x = x_6$. The length of area of mixed structure is determined in the following way

$$x - x_5 \approx 0.09\sqrt{\kappa\cdot t}\,. \tag{16}$$

To calculations we assume, that

$$x - x_5 \cong 0.1\sqrt{\kappa\cdot t}\,. \tag{17}$$

4. Analysis of results

In Fig.4 graphs representing the results of calculations of $x = x_6 = x(t)$ HAZ and ranges x_2, $x_{3,}$ x_4.i x_5 calculated from equations (8)-(17) are shown. For a given and properly set time t, the differences of x among curves, according to formulas (8), (9), (11), (13), (15) and (17), determine the estimated values of the length of HAZ components, according to Fig. 1.

From the graphs can be seen that the size of HAZ components increases with the increase of time of action t. So the determination of time t is crucial. As it could be expected on the basis of the phenomena of diffusion and heat conduction, if the of action t tends to infinity, the areas of HAZ components aim to infinity meaning to mall half-space and conversely, when time t aims to zero, then HAZ and its components tend to zero.

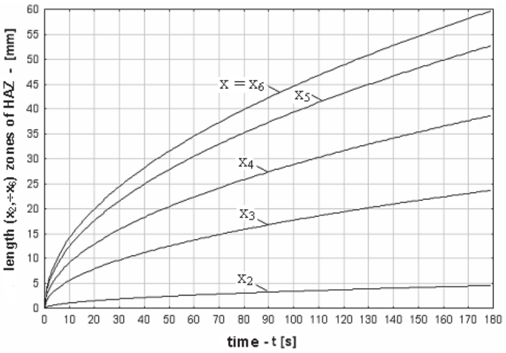

Fig. 4. Graph of changes of HAZ and its components for carbon steels depending on the time t of temperature T_0

Practical and useful procedure when using this method of calculation is as follows: for a given type of welding process and for the conditions in which it takes place, and on the basis of experience, the knowledge and skills one should determine the time t of action of maximum temperature T_0 in a point of head area of welded material or in half-space, see Fig.3.

5. Concluding remarks

1. An analytical method to estimate the HAZ, its components and these areas for welding of carbon steels is presented. It results from the graph in Fig. 4 that these areas increase with increasing time *t* of temperature T0 on the front surface of the welded material. The calculations are limited to the maximum time t of 180 seconds. For anticipated times longer than 180 seconds, formula (1) should be used directly for calculations and then the respective areas of x, x_2, x_3, x_4, and x_5 should be calculated.
2. For other welded materials such as steel alloys or non-ferrous metals and their alloys analogous equations as for carbon steel can be easily obtained with prior knowledge of HAZ scheme and plot of phase transitions as in Fig. 1. However, the melting point of the welds T_0 and the temperatures T, in which does not occur in the welded material any changes of internal structure must be given. The temperature limits for components of HAZ and the diffusion coefficients of heat κ should be indicated and also times t of action of maximum temperature T_0 on face area of welded material should be determined. In the future one will be able to draw appropriate nomograms, by means of which one could easily read calculated values of x, x_2, x_3, x_4, i x_5.
3. As it is known, homogeneous temperature field T_0 acting on the surface triggers the temperature gradient inside the welded material thereby causing the formation of thermal stress field from the distribution of the temperature and phase transformation between the component zones [15-20]. However, analysis of such fields of stress and of elastic-plastic deformations during such heating requires the use of complex analytical methods of the theory of thermal stresses, which take into account the effect of phase transformations and it was not the subject of this work.
4. In multi-layer joints, which include high-pressure pipelines, the formation of the internal structure (and hence the properties) is highly influenced by complex thermal cycle. The obtaining of highly dispersed structure that ensures good immediate strength properties of connection depends on speed of heat dissipation during welding and the presence of substructures associated with deformation during welding. The choice of appropriate technology of welding and heat treatment of thick-walled pipes made of steel decisively influences the level of creep resistance (high-temperature creep strength) of welded connections. Technique of stacking stitches is of great importance for the creep resistance of the weld joint is. During welding a multilayer (multi-stitch), see [10, 11], a process of improving the inner layers by successive located closer to the surface takes place and time *t* of action of temperature *T*o is the sum of component times of single layers (stitches).
5. Our study does not take into account the effects related to the heating of materials before welding, since it is assumed that the heating temperature is lower than 600°C and therefore such heating does not affect the HAZ. The preheating temperature certainly influences the size of the resulting temperature gradient, the distribution of welding stresses and strains, on the kinetics of heating and cooling processes and many others, but these phenomena, as mentioned before, are not the subject of this work.
6. In conclusion, it should be added that in the case of materials (steel) designed to operate at elevated temperatures, one should oppose crushing of grains due to welding.S uch a structure arises in the HAZ and reduces the time strength (creep strength) of welded elements, because a large number of grain boundary enhances diffusion process on the grain boundaries [2]. Ideally, the preferred case would be the lack of HAZ, however, in practice it seems impossible. In order to reduce the negative impact of the HAZ on work of welded joint some heat treatments such as annealing or relaxing with the transition in the form of carbides within the matrix grains. The area with the most unfavorable elastic properties and resistance to impact is an area of coarse structure CGHAZ.
7. In order to increase the efficiency of the welding process it is desirable to increase the amount of heat introduced into the joint, but on the other hand, increasing the amount of heat introduced into the joint results in deteriorating of plastic properties of CGHAZ, see [10, 11].
8. In order to describe mathematically the changes in the structure and phase transitions in the HAZ during welding thermal cycles (real or simulated) or in annealing processes or other heat treatment processes, appropriate kinetic equations of these changes should be considered, see eg [15-20]. Considering only the equation of thermal conductivity is insufficient. Noteworthy here are, as already mentioned in the introduction, Łomzik's works [10, 11] on the structural changes and the physical-mechanical properties of HAZ (mainly CGHAZ area). For alloy steels 13HMF and P91 this area was subjected to repeated thermal cycles of welding at different T_{max} and different cooling times $t_{8/5}$ (various speeds of cooling). In these studies parameters T_{max} and cooling time, for example $t_{8/5}$ are essential; similarly as T_0 (melting point of a binder) and time t of heating with maximum temperature ($T_0 = T_{\mathrm{max}} = \mathrm{const}$) of face area of Jominy's rod (in our case the face of half-space) during studies of the HAZ and its component areas.
9. According to [10], subjecting the coarse-grained HAZ of 13HMF steel after long operation, of cycles of thermal impact with a tempering effect, influences the improvement of their plastic properties and the best results are obtained for a short $t_{8/5}$ cooling times, for example for 6 seconds. For this steel, subjecting coarse grain HAZ to thermal cycles of tempering character will improve their plastic properties.

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