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NEW ALGORITHMS FOR THE OPTIMIZATION OF WELDING STEEL MATERIALS BY CALCULATING THE PREHEATING TEMPERATURE

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Abstract. By studying the welding process, it was determined that most formulae do not provide accurate results for the preheating temperature and critical cooling rate. The process of calculating the preheating temperature based on the critical cooling rate has proven to be unreliable, since in most cases it leads to deviations. This has motivated the authors to introduce the cooling rate into the procedure of welding design. That is why the mathematical procedure determines the accuracy of the general formula for the cooling rate, based on which we can precisely determine the value of the preheating temperature. The authors' intention is to mathematically present the thermal processes as much as possible, to support the assumption that this leads to a better analysis and a better understanding of the physical process and optimization of the welding process.

Keywords: cooling time, temperature, welding, preheating temperature, cooling rate.

1. INTRODUCTION

The subject matter of this research is welding, as presented in, e.g., [1−16], which provides the conditions for the calculation of the critical cooling rate, preheating temperature and cooling rate during welding. A new solution for the critical cooling rate and preheating temperature will be presented.

The general papers in this field were studied, as referred to in [17, 21], and the papers published by the authors [22–27], have led to new approaches to the solution to the problem of welding and the calculation of its key variables. It should be pointed out that the main results of the work are that the results determined here have helped to determine and introduce a new method and formula for determining the critical cooling rate after welding.

This paper deals with the derivation of accurate formulas and methods for calculating the critical cooling time and preheating temperature. This is because the formulas used in the literature are only rough approximations. They produce bad structures in the welds of steel materials after welding. In addition, these formulas are applicable to several types of welding, such as:

Gas welding: oxyacetylene welding (OAW). − Arc welding: shielded metal arc welding (SMAW), gas-tungsten arc welding (GTAW), plasma arc welding (PAW), gas-metal arc welding (GMAW), flux-cored arc welding (FAW), submerged arc welding (SAW), and electro slag welding (ESW). − High-energy beam welding: electron beam welding (EBW) and laser beam welding (LBW). Since an electric arc is not involved in the electro slag welding process, it is not exactly an arc welding process.

In addition to these types of welding, the results can be freely used in inductive high-frequency welding of steel pipes, where good results have been achieved. In addition, effects in welding that were not known until now have been discovered.

The development of an analytical dependency for the temperature of cooling will be obtained, based on [17–21, 28]. For example, for two steel plates to be welded, the temperature distribution can be described by an equation known as the Fourier equation.

$$\frac{\partial T}{\partial t} = a\left(\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2}\right) \tag{1}$$

where the coefficient of temperature conduction is given by

$$a = \frac{\lambda}{c\gamma} \tag{2}$$

where c is the specific heat and γ is the specific mass.

If the temperature T does not depend on z, welding is done along the x-axis. The source of heat is a volume with base dxdy and height d. According to [17–18], a solution of equation (7) is

$$T(r,x) = \frac{q}{2\pi\lambda d}\exp\left(-\frac{vx}{2a}\right)K_0\left[r\left(\frac{v^2}{4a^2}+\frac{b}{a}\right)^{0.5}\right] \tag{3}$$

where K_0 is the modified Bessel function of the 2nd kind and 0 class. Since the case of Arc welding includes cases with higher values of q, equation (3) can be transformed to

$$T(y_0,t) = \frac{q}{vd\sqrt{4\pi\lambda c\gamma t}}\exp\left(-\frac{y^2}{4at} - bt\right) \tag{4}$$

where d is the thickness of the plates [m], q is the input heat [$\mathrm{J\,m^{-1}}$], v is the welding speed [$\mathrm{m\,s^{-1}}$], t is the time [s], $b = 2h/cd\gamma$ [$\mathrm{s^{-1}}$] (h is the coefficient of the heat transfer), the quantity y represents the distance of the heat source [m], λ is the thermal conductivity [$\mathrm{J\,s^{-1}\,m^{-1}\,°C}$], c is the specific heat [$\mathrm{J\,kg^{-1}\,°C^{-1}}$], and γ is the specific mass [$\mathrm{kg\,m^{-3}}$].Equation (4) holds when the highest speed of cooling is in the welding zone. Hence, $y=0$ and $\exp(-bt)=1$, so

$$T(t) = \frac{q}{vd\sqrt{4\pi\lambda c\gamma t}} \tag{5}$$

The cooling time $t_{8/5}$ for arc welding can be defined as the difference between t_5 and t_8, where t_8 is the time when $T(t)$ reaches 800°C by cooling and t_5 is the time when it reaches 500°C

$$t_{8/5} = t_5 - t_8 \tag{6}$$

When $t_{8/5}$ is less than the effective value for welded steel, preheating at temperature T_p should be performed. The times t_8 and t_5 can be calculated if equation (11) is squared and solved by

$$t = \frac{q^2}{v^2 d^2 4\pi\lambda c\gamma}\frac{1}{(T-T_p)^2} \tag{7}$$

Putting $T=800$°C in (7) will provide t_8, and using 500°C will provide t_5 in the forms (8) and (9):

$$t_8 = \frac{q^2}{v^2 d^2 4\pi\lambda c\gamma}\frac{1}{(800-T_\mathrm{p})^2} \tag{8}$$

$$t_5 = \frac{q^2}{v^2 d^2 4\pi\lambda c\gamma}\frac{1}{(500-T_\mathrm{p})^2} \tag{9}$$

If (8) and (9) are used in (6), this will yield equation (10), which presents the 2D Rosenthal model for calculation of $t_{8/5}$ ($q = Qv$).

$$t_{8/5} = \frac{Q^2}{4\pi\lambda\gamma c d^2}\left[\frac{1}{(500-T_p)^2} - \frac{1}{(800-T_p)^2}\right] \tag{10}$$

Formula (10), whose numerical results yield significant deviations from experiment, has been used for a long time, to this very day. And it is used and quoted in numerous papers, books and even doctoral dissertations worldwide. British Standard [29] carried out certain improvements on the 2D and 3D modeling [17, 20]; however, in some examples there are once again significant deviations which hinder the welding technology.

2. AN ESTIMATE OF THE MORE ACCURATE EXPRESSIONS FOR THE CALCULATION OF CRITICAL VARIABLES IN WELDING

The authors of this paper have determined that relation (10) does not provide correct values in many instances of application. So in case when the heat release is in the edge of the weld, equation (4) becomes

$$T(t) = \frac{q}{vd\sqrt{4\pi\lambda c\gamma t}}\exp(-bt) \tag{11}$$

Determining the deviations of equation (5) from (11) was carried out thoroughly and in great detail in [27]. This indicates that it is of great importance to obtain an equation which provides new values for $t_{8/5}$ and T_p under the condition that the preheating temperature behaves according to equation (11). Let us square equation (11), introduce the preheating temperature of T_p and solve for t. Then we obtain

$$t = \frac{q^2}{v^2 d^2 4\pi\lambda c\gamma}\frac{\exp(-2bt)}{(T - T_p)^2} \tag{12}$$

Putting $T = 800$°C in (12), we obtain the value for t_8 in the form

$$t_8 = \frac{q^2}{v^2 d^2 4\pi\lambda c\gamma}\frac{\exp(-2bt_8)}{(800 - T_p)^2} \tag{13}$$

In the case where the temperature curve of the cooling intersects with the value of 500°C, the following relation is obtained:

$$t_5 = \frac{q^2}{v^2 d^2 4\pi\lambda c\gamma}\frac{\exp(-2bt_5)}{(500 - T_p)^2} \tag{14}$$

By applying relation (6) and following the replacement of the known variables we obtain an equation which is accurate and as such it changes equation (10), and in addition also changes the equation for the 3D model and all the equations related to it in the British Standard

$$t_{8/5} = \frac{Q^2}{4\pi\lambda\gamma c d^2}\left[\frac{\exp(-2bt_5)}{(500 - T_p)^2} - \frac{\exp(-2bt_8)}{(800 - T_p)^2}\right] \tag{15}$$

Furthermore, the equations for the 2.5 D and 3.5 D model from [31] also undergo a change, where the attempt to find a universal and correct relation was unsuccessful. All these claims were confirmed in a paper published in the journal [27].

However, in the case when the welding includes heat release from the weld, then we must calculate using relation (4), where we obtain, as in the previous case,

$$t = \frac{q^2}{v^2 d^2 4\pi\lambda c\gamma}\frac{\exp\left(-\frac{y^2}{2at} - 2bt\right)}{(T - T_p)^2} \tag{16}$$

Putting $T = 800$°C in (16), we obtain the following value for t_8:

$$t_8 = \frac{q^2}{v^2 d^2 4\pi\lambda c\gamma}\frac{\exp\left(-\frac{y^2}{2at_8} - 2bt_8\right)}{(800 - T_p)^2} \tag{17}$$

And for t_5, we obtain

$$t_5 = \frac{q^2}{v^2 d^2 4\pi\lambda c\gamma}\frac{\exp\left(-\frac{y^2}{2at_5} - 2bt_5\right)}{(800 - T_p)^2} \tag{18}$$

By using (17) and (18) in (6) we obtain a new value for the critical cooling rate

$$t_{8/5} = \frac{Q^2}{4\pi\lambda\gamma c d^2}\left[\frac{\exp\left(-\frac{y^2}{2at_5} - 2bt_5\right)}{(500 - T_p)^2} - \frac{\exp\left(-\frac{y^2}{2at_5} - 2bt_5\right)}{(800 - T_p)^2}\right] \tag{19}$$

which represents a universal and accurate formula which determines the relation between the critical cooling rate and the preheating temperature. Relation (19) changes all the approximative equations known so far, with the addition that it is exact since it provides accurate results.

Being aware of the lack of a general expression for the cooling rate in welding, the theoretical approach focused on the calculation and identification of a relation which will help researchers and experts involved in practical work in the field of welding. The procedure begins with a general expression for the welding temperature

$$T(y,t) = \frac{q}{vd\sqrt{4\pi\lambda c\gamma t}} \exp\left(-\frac{y^2}{4at} - bt\right) \tag{20}$$

where the variables are predefined, by introducing the concept of cooling rate as the first value of temperature $T(t)$ in the function of time t

$$W_0 = \frac{\mathrm{d}T(t)}{\mathrm{d}t} \tag{21}$$

After the differentiation of (20),we obtain the expression for the cooling rate

$$W_0 = \frac{q}{vdt\sqrt{4\pi\lambda c\gamma}} \exp\left(-\frac{y^2}{4at} - bt\right)\left[\left(\frac{y^2}{4at^2} - \mathrm{b}\right)\sqrt{t} - \frac{1}{2\sqrt{t}}\right] \tag{22}$$

where after certain changes we obtain

$$W_0 = \frac{q}{vd\sqrt{4\pi\lambda c\gamma t}} \exp\left(-\frac{y^2}{4at} - bt\right)\frac{\sqrt{t}}{t}\left[\left(\frac{y^2}{4at^2} - b\right)\sqrt{t} - \frac{1}{2\sqrt{t}}\right] \tag{23}$$

By putting expression (20) in (23) we obtain

$$W_0 = T(y,t)\left[\frac{1}{2t}\left(\frac{y^2}{2at} - 1\right) - b\right] \tag{24}$$

Since we are interested in introducing the preheating temperature prior to welding at a temperature of T_p, the following relation is rendered more accurate

$$T(t) + T_p = 800°\mathrm{C} \tag{25}$$

which by putting (25) in (24) gives

$$W_0 = \left(800°\mathrm{C} - T_p\right)\left[\frac{1}{2t}\left(\frac{y^2}{2at} - 1\right) - b\right] \tag{26}$$

Finally, from expression (26) we can calculate the preheating temperature T_p

$$T_p = 800°\mathrm{C} - \frac{W_0}{\frac{1}{2t}\left(\frac{y^2}{2at} - 1\right) - b} \tag{27}$$

which with the necessary changes, gives us

$$T_p = 800°\mathrm{C} - \frac{2tW_0}{\frac{y^2}{2at} - 2bt - 1} \tag{28}$$

In the existing literature [31] and practice, the following formula for calculating the cooling rate was used

$$W = \frac{300}{t_{8/5}} \tag{29}$$

where $t_{8/5}$ is the critical cooling rate in seconds after welding, and represents the period when the cooling temperature decreases from a value of 800°C to a value of 500°C. Formula (29) is an approximation, so that in the case of the application of welding designs in practice it offers incorrect results.

A poor approximation of the cooling rate leads to very little time for releasing excess carbon from the weld, which, according to Shuman [13], makes such a structure prone to brittle fractures and breaking. References [32–43] use well-known relations which provide deviations from some of the ranges of the relevant variables, and the attempt at using the CE equivalent provides results only for certain groups of steel and thus cannot be considered general and with a good application.

References [44–49] use, in addition to the well-known theory, the results of experimental research. By studying the literature, the authors of this paper reached the conclusion that most authors express the known accepted theory, but when it is time to present results, often the tables recommended by the manufacturers of certain types of steel are used.

Contrary to that, a newly-estimated formula for the calculation of the cooling rate and adequate values for preheating temperature T_p, enables such a dependence of the cooling rate $T(t)$ that there will be enough time $t_{8/5}$ to expel the excess carbon C [wt%] from the weld. Finally, the weld will, after the welding process and optimal cooling rate, have a suitable chemical composition, from which good mechanical features will ensue.

Formulae (19) and (24) represent general expressions for the cooling rate, where application in practice can be used to optimize various types of welds. The contribution of this work lies in the fact that by applying simple formulae in practice, ones that are quickly calculated, favorable results are obtained without the possession and application of expensive FEM packages for the simulation and modelling of welding.

3. RESULTS

3.1. Calculation of the exact values of the critical cooling time and preheating temperature

In order to evaluate the results of the method proposed in this paper, it is necessary to calculate the cooling rate which is given in relation (20), at a point when the temperature of 800°C is reached. It has been proven that it is not sufficient to provide or calculate the critical cooling time, and instead, what is important is to find the time t when the curve $T(t)$ intersects with the value of 800°C.

Then we can calculate the cooling rate of the weld based on the new formula from this paper (23), and so if it is greater than the critical rate, preheating must be introduced for the welding strips. This is possible since most of the manufacturers offer data on the critical cooling rate for their steel materials in their technical specifications. This must be taken into consideration since on the contrary, the weld will be a brittle structure [13].

For a certain example of welding, it is necessary to calculate the time t according to equations (23) and (24) for which the critical cooling rate is achieved. Unfortunately, the equations are of a transcendental type and it is impossible to solve them explicitly. Considering the fact that we want to avoid the application of a simulation package, a simple iterative Newton method will be introduced.

Newton's iterative method for solving the equation $f(t)=0$ is

$$t_{i+1} = t_i - f(t_i)/f'(t_i) \tag{30}$$

$i=1,2,3$, where i indexes the iteration arrived at, $f(t_i)$ is the function from which t_i is calculated, and $f'(t_i)$ is the first derivative of the function. The iteration process $i=0$ begins with the selection of values which are expected. Due to the good convergence of the iterative process, even using a poor initial solution, the procedure finds a solution for t by the second or third iteration. Let us form the function $f(t)$ in the form

$$f(t) \equiv W_0 \frac{q}{vd\sqrt{4\pi\lambda c\gamma t}} \exp\left(-\frac{y^2}{4at} - bt\right)\frac{\sqrt{t}}{t}\left[\left(\frac{y^2}{4at^2} - b\right)\sqrt{t} - \frac{1}{2\sqrt{t}}\right] = 0. \tag{31}$$

In order to apply the procedure for calculating the preheating temperature, after previously determining the critical cooling rate, we will carry out a project of welding on a concrete example.

***Example* 1**. It is necessary to weld steel strips $d=7.4$ mm thick, at which point the following amount of heat is introduced: $q_1=16916$ J/cm. Heat release takes place in the vicinity of the weld. The necessary preheating temperature in the following cases of critical cooling rates needs to be calculated $W_0=10$ C/s. After putting the known values of the temperature and the cooling rates (11) and (24) in the following order, we get

$$T(t) = \frac{q}{vd\sqrt{4\pi\lambda c\gamma t}}\exp(-bt) = 4990.t^{-0.5}\exp(-0.0125t) \tag{32}$$

$$W_0 = -T(y,t)\left[\frac{1}{2t}\left(\frac{y^2}{2at}-1\right)-b\right] = -T(t)\left(\frac{1}{2t}+0.0125\right) \tag{33}$$

where $T(t)$ is given by equation (32).

To apply the iterative procedure on relation (30), the function $f(t)$ is defined by relation (31). It is further necessary to find the first derivative of the function (31), which for our example takes the form

$$f'(t) = \exp(-bt)\left(b^2t^{-0.5}+bt^{-1.5}+\frac{3}{4}t^{-2.5}\right) \tag{34}$$

By replacing (34) and (31) in (30), with the changes in the known variables, then performing the iterative procedure, the following results were obtained:

$$t_0 = 50\text{ s};\ \ t_1 = 44.373\text{ s};\ \ t_2 = 45.011\text{ s} \ \text{ and } \ t_3 = 45.021\text{ s}.$$

By applying the results of the iterative procedure and formula (28), we obtain the required values for the preheating temperature: $T_p = 376°\text{C}$.

We can draw the conclusion that for the smallest critical cooling rate of 10°C/s the greatest preheating temperature of 376°C must be introduced. With the increase in the critical cooling rate, there is a decrease in the required preheating temperature.

3.2. Procedure for calculating the preheating temperature for the approximate welding temperature

Calculating the preheating temperature by (10) is complicated and incomplete, so a new kind of calculation will be introduced. Starting from equation (5), which can be differentiated with respect to t, the expression for the speed of cooling after welding will be determined in the form

$$W_0 = \frac{\mathrm{d}T(t)}{\mathrm{d}t} = \frac{q}{2vd\sqrt{4\pi\lambda c\gamma t^3}} \tag{35}$$

Equation (35) can be transformed into

$$W_0 = -\frac{q}{vd\sqrt{4\pi\lambda c\gamma t}}\frac{1}{2t} \tag{36}$$

After substituting equation (10) into (36), we obtain

$$W_0 = -T(t)\frac{1}{2t} \tag{37}$$

This shows that the speed of cooling can be obtained by multiplying the values of $T(t)$ by the factor $(1/2t)$. In order to conduct the preheating, there should be an increase of the value $T(t)$ for the temperature of the preheating. In this way, the value of this temperature would be 800°C, which implies that (37) becomes

$$T_p - 800 = -2W_0t \tag{38}$$

and

$$T_p = 800 - 2W_0t. \tag{39}$$

Knowing W_0, and then squaring (35), the following equation for t can be found:

$$\mathrm{W}_0^2 = \left(\frac{q}{vd}\right)^2\frac{1}{16\pi\lambda c\gamma t^3}. \tag{40}$$

If (40) is used for finding a solution for t, the following, and final, formula will be obtained:

$$t = \sqrt[3]{\frac{q^2}{16\pi\lambda c\gamma(vdW_0)^2}}\ . \tag{41}$$

After conducting a preheating to this temperature, new values for the time when the function $T(t)$ reaches 800°C and 500°C can be calculated.

***Example* 2**. In the case of Arc welding of steel tape with a thickness of $d = 14$ mm, a heat of $q_1 = 1.25$ kJ/cm is in place. The speed of cooling of this steel material is known: W_0=20°C/s. Then we can calculate the times t_8, t_5, $t_{8,5}$, the speed of cooling for the applied regime, and eventually the temperature of preheating of the steel material before welding.

Application of equation (8) provides

$$t_8 = 0.00744 \cdot 10^{-13} \frac{q_1^2}{d^2} = 5.93 \text{ s}, \tag{42}$$

while equation (9) provides

$$t_5 = 0.019048 \cdot 10^{-13} \frac{q_1^2}{d^2} = 15.18 \text{ s}. \tag{43}$$

Depending on the values for t_8 and t_5, the time of cooling can be calculated:

$$t_{8,5} = t_5 - t_8 = 15.18 \text{ s} - 5.93 \text{ s} = 9.25 \text{ s}. \tag{44}$$

The speeds of cooling at these specific points for the calculated time t can be calculated, which further provides

$$W(5.93) = 67.45 \text{ °C/s}. \tag{45}$$

According to the numerical results, it can be seen that when the cooling temperature reaches 800°C, the speed of cooling reaches 67.45°C/s. Due to the fact that this is significantly larger than the value applied to steel material for welding in practice, which is 20°C/s, it can be concluded that a preheating of the material needs to be carried out. This calculation and conclusion is significantly more correct than the formula in [34].

This type of task can be solved in two ways: graphically and analytically. Fig. 1 presents a graph of the behavior of the cooling temperature and speed of cooling as functions of t for this task. The graph shows the values for t_8 and t_5, and they are the same as calculated in this case, but an analytical solution yields more precise results. However, the deviations are small and inevitable in practice. According to the graph in Fig. 1, the cooling rate $W(t)$ decreases faster than the cooling temperature $T(t)$.

The procedure of graphical solving can be carried out by placing a line parallel to the abscissa axis for the speed of cooling of 20°C/s. Furthermore, the abscissa axis includes time in seconds and its value is 13.4 s.

From the point of time of 13.4 s, the straight line parallel with the ordinate axis can be drawn to the intersection with the curve which presents a cooling temperature of $T(t)$. Hence, it provides a certain value. The difference between 800°C and the temperature at $T(t)$ is the value for the temperature of preheating T_p while the temperature from the graph is nearly 265°C.

In order to provide more correct and complete analysis and to demonstrate the application of the algorithm, the analytical solution of this task will be provided. The presented equations can be used to calculate the required time t to obtain the preheating temperature.

$$t = \sqrt[3]{\frac{q^2}{16\pi\lambda c\gamma(vdW_0)^2}} = 13.32 \text{ s}. \tag{46}$$

Knowing the calculated time of 13.32 s, the simple equation (39) can be used for the preheating temperature

$$T_p = 800 - 2W_0 t = 267 \text{ °C}. \tag{47}$$

In this way, the calculation and planning of Arc welding can be completed. After the introduced preheating of 267°C, a structure very close to the basic material can be obtained. This procedure avoided a martensitic structure as in [37–38], because the application of the preheating calculated by the standard method [29] and the method of Yto Besio from [39] provided a preheating temperature of 155°C, which is insufficient.

The authors of the mentioned works used a metallographic analysis for determining that the weld has a martensitic structure, which implied a good preheating. Therefore, the results of this work offer an answer as to why there is a difference in weld regarding basic material. In other words, it is answered why an increased carbon content and martensitic structure are developed.

This paper offers a comparison with the results from one work. However, the authors of that work found many works without any precise definition of the parameters of the Arc welding, such as the time of cooling and preheating temperature.

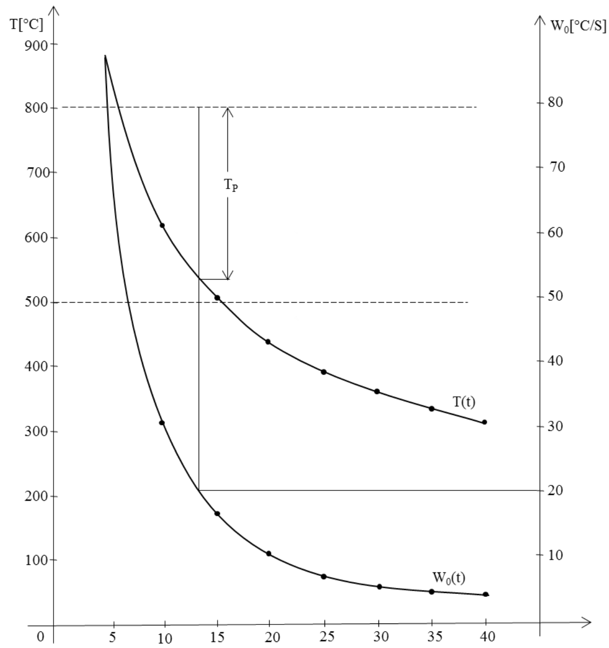

Fig. 1 – Graphs of temperature and speed of cooling and presentation of determination of preheating temperature. (Abscissa represents time in seconds.)

Accordingly, the method presented in this paper, through a new formula for the cooling rate (37), determined that it is at the intersection of $T(t)$ with 800°C that the cooling rate is equal to the critical cooling rate, which can be determined based on the type of steel. In this way during the entire period of critical cooling speed, all the excess carbon is emitted, which guarantees a good quality weld.

In addition to the exact expressions for calculating the preheating temperature (46) and (47), Fig. 1 shows the graphical method of determination. The left ordinate axis represents the welding temperature T and the right the cooling rate W after welding. The abscissa axis is the time axis t in seconds.

In the presented example of welding design, an analytic calculation and graphical determination of the preheating temperature was carried out in a new and original way. These research results will enable a complete welding which provides a homogenous structure. The existing methods, which relied on a system of calculating the preheating temperature by using the critical cooling time and an average fixed cooling rate, led to poor and brittle, low quality welds.

4. DISCUSSION

In the previous presentation and verification of the derived methods and formulas, two examples were presented. Example no. 1 refers to several types of welding of two steel plates where the critical cooling time and preheating temperature are calculated. In Example no. 2, a new formula is derived for calculating the mentioned parameters in high-frequency inductive welding of steel pipes. Both methods shown give accurate results. In several examples, this was confirmed by comparison with the FEM method and the method of direct measurement using thermocouples. The methods have been tested by comparing them with many examples from practice that are the result of experimental research.

Examples of the calculation of the mentioned welding parameters will be shown in several examples from practice. Several examples will be chosen for which the exact data are first calculated according to the results from this paper. Then, already known formulas that have been used for a long time in practice will be applied. In order to evaluate the accuracy, the percentage relative error of the deviation will be calculated. The sorted data are given in Table 1.

Table 1

Examples of welding steel plates with a thickness of 7.4 mm

no	speed	heat	Pr.temp.	1.$t_{8/5}$	2.$t_{8/5}$	Eror	3.$t_{8/5}$	Eror	4.$t_{8/5}$	Eror	5.$t_{8/5}$	Eror
1	0.172	13.37	273	36	44.	23	273	658	219	508	133	269
2	0.17	13.61	280	36	47.	31	304	744	229	536	169	369
3	0.136	16.9	185	27	39	44	206	663	167	518	133	393
4	0.208	11.1	180	31.6	20.	36	84.9	169	71	125	56	77
5	0.19	12.1	178	22.15	23	3	100	351	84	279	66	198
6	0.183	12.6	178	23.06	24.	4	107	364	91	295	72	212
7	0.215	10.7	169	20	18.	9	73	265	60	200	50	150
8	0.15	15.3	180	27	32.3	22	163	504	136	404	107	296

Table 1 presents sorted data for eight examples of welding steel plates with a thickness of 7.4 mm, where the second column shows the welding speed [mms^{-1}], column 3 is the amount of heat input [kJcm^{-1}] and column 4 is the preheating temperature [^{0}C]. Further, in column 1, $t_{8,5}$ represents the exact value using the method of this paper [s], column 2 presents the results according to the method of [39], and right behind it is the column for the relative error [%], as shown in Fig. 2.

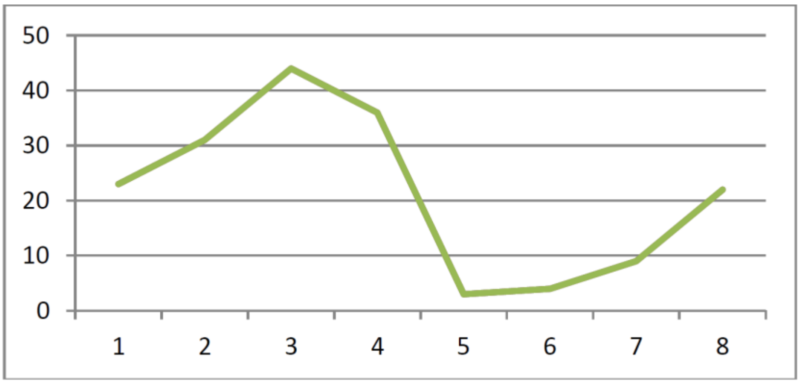

Fig. 2 – Percentage deviation according to the method from [39].
The abscissa presents sample numbers and the ordinate presents the relative error [%].

Column 3 gives the calculation according to reference [34] using the 2 D method whose graph is shown in Fig. 3.

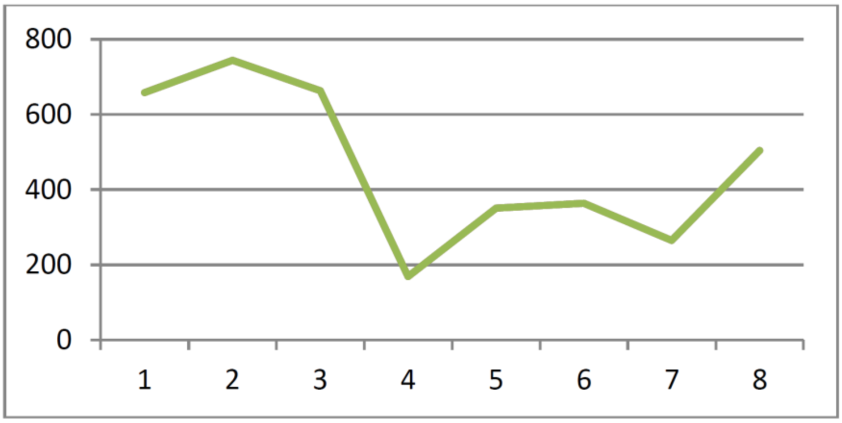

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Fig. 3 – Percentage deviation according to the method from [34].
The abscissa presents sample numbers and the ordinate presents the relative error [%].

Column 4 gives the calculation according to reference [29] using the 2 D BS method whose graph is shown in Fig. 4.

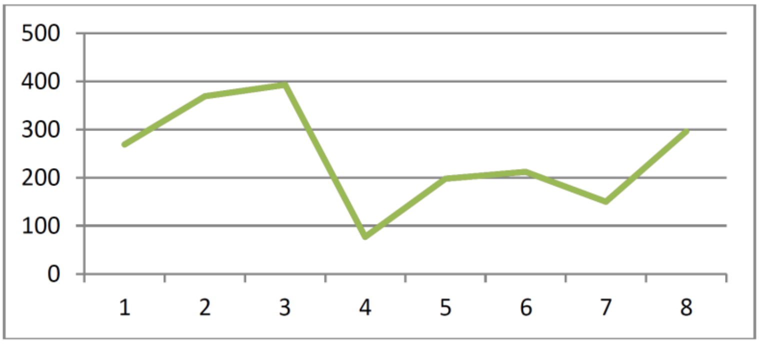

Fig. 4 – Percentage deviation according to the method from [29].
The abscissa presents sample numbers and the ordinate presents the relative error [%].

Looking at the numerical data behind Table 1 and the corresponding pictures, the conclusion is that the formulas used so far made big mistakes.

Therefore, the significance of the presented and researched formulas of this work is significant both theoretically and practically. Direct evidence of the practical accuracy of the applied results presented here can be found by looking at the paper [27], which accurately determines the preheating temperature. This is practically proven by the results in the paper [50], where it can be seen that at a well-defined preheating temperature, the chemical composition does not change radically. Otherwise, there are large and negative consequences.

5. CONCLUSION

In the paper we identified the default of the existing theory regarding any connection between the critical cooling time and preheating temperature. As a result, researchers and experts in the field of welding technology calculated the needed variables, with results deviating from the accurate ones. By applying such results in practice, no high quality weld was obtained. The products of this process deviated from the basic standards, and so experiments were resorted to. However, such research rarely yielded positive results.

In addition to the shortcomings in determining the critical cooling time, the dynamics of the welding process were also neglected. Thus, an a priori approach was made, assuming that during the critical cooling time, the cooling rate was constant, which provided for a rough approximation with negative consequences for the welding process.

The authors of this paper, by analyzing and studying the extensive literature that covered an extensive period of time relevant for this field, along with extensive research applied in practice, came to the idea of estimating an accurate general formula which would be accurate in calculating the ties between the critical time and the preheating temperature.

This result provided the basis for the realization of the authors' idea of developing a general formula which could be used to calculate the cooling rate of a weld following welding. Then an elementary mathematical operation was used to estimate an original and new connection between the preheating temperature and the cooling rate.

The new procedures were applied to a particular example of welding, at which point the preheating temperature was determined based on the predetermined critical cooling rates. In addition to the analytical estimation process, a graphical procedure was provided for determining the described variables in welding. The new results are being offered to a global public for use and evaluation, for which the authors will be most thankful.

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