A COMPUTER PROGRAM FOR PREDICTING THERMAL CYCLES AT THE HAZ OF BEAD ON PLATE WELDS USING DIMENSIONS OF THE MOLTEN OR HEAT AFFECTED ZONE AS INPUT DATA

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Abstract. *There are some analytical solutions of the heat conduction equation that can be used in estimating thermal cycles suffered by the material in the heat affected zone (HAZ) of bead on plate weldments obtained by arc processes. The simplest of them consider a concentrated heat source traveling over a semi-infinite medium. More elaborate ones take into account that heat transfer from the arc to the plate takes place through a finite area. These more elaborate solutions represent more accurately the temperature field established during the welding process, but they need information about the size of the heat exchange area and/or the distribution of the heat flux over this surface. In this paper a procedure for estimating the heat flux distribution parameter (analogue to the standard deviation) used in a solution for a plate that receives a gaussian distribution of heat flux in one of its surfaces is described. The dimensions of the molten zone are used as input data in this procedure. Besides the heat flux distribution parameter, the procedure provides a value of thermal efficiency for the weld. With the output data of this procedure and the plate material properties (also used by this procedure) it is easy to calculate the thermal cycles using the considered solution of the heat conduction equation. The present paper also describes a graphical user interface designed to assist the measurement of the molten zone (in a digitised weld macrograph) and the selection (using the same image) points in the HAZ where the thermal cycle predicted by the analytical solution is to be computed.*

Keywords*: Welding, Heat conduction, Welding metallurgy*

1. Introduction

There are many analytical solutions available for predicting the heat conduction that takes place in a plate being welded. Most of these solutions do not take into account variations in the thermophysical properties of the plate material, do not model the reinforcement due to the material added from the filler metals and are not able to represent any geometry different from a plain plate (no gap at the joints). Even so they are widely applied, specially in the study of phase transformations during bead on plate welding (where there are no joint at all) performed for research in welding processes and metallurgy. Among these solutions, the most widely known are those due to Rosenthal (1941), that describe a traveling concentrated heat source over a semi-infinite three-dimensional medium or in an infinite two-dimensional medium, which use is illustrated in Connor (1987).

The Rosenthal solutions are the most easy to derive and use, but lack ability to describe realistically the distribution of heat flux that enters the plate (producing frequently, on thick plates, molten zones having cross-section very far from the circles predicted by the Rosenthal solution for these plates) need semi-empirical corrections to deal with plates that are not very thin nor very thick and disregard the heat loss to the environment (the heat is conducted only inside the plate). Solutions able to deal with distributed heat sources, finite thickness plates and heat losses through the plate surfaces require a more elaborate computational implementation and also more input data, for describing the distribution of heat entering the plate and the heat losses through the plate surfaces. Estimating the heat losses to the environment, by conduction through the plate support, by convection through any surrounding fluid and by radiation is a challenge outside the scope of the present work. And for relatively thick plates immersed in still air, the heat flux by conduction inside the plate is much greater than the losses though the plate surfaces (making them almost negligible). So, the main point in this paper is really the estimation of a parameter describing the distribution of heat flux that enters the plate for melting part of it. It is important to note (the mathematical expressions in the beginning of the next section should help in making this clear) that given the heat flux distribution parameter, the estimation of the welding thermal efficiency is trivial.

In the present paper the procedure for estimating the heat flux distribution parameter proposed by Santos (2001) will be adopted. That procedure was developed for a specific model of the heat flux distribution entering the plate heated surface that is the circular gaussian function. Its results can be used as input data for some different analytical solutions of the heat conduction inside the welded plate that uses this same heat flux distribution model, as that proposed by Santos *et al.* (1999), that appears with a typing error in that paper, but is correctly written in Santos (2001) and Santos *et al.* (2000a).

A second point in the present work is the development of a graphical user interface that makes easier the input of weld cross section geometrical data and the choice of the points were the thermal cycle is to be calculated. It is difficult to measure distances directly on a macrograph and, after having done this, it is not easy also to visualize where in that macrograph will fall each point of the coordinates system that must be associated with it in order that an analytical expression for the thermal cycles could be used.

The final objective of this work is to offer an adequate computer implementation of: (i) a good analytical expression for calculating thermal cycles to which the HAZ of a bead on plate weld was subject, (ii) a procedure for estimating the heat flux distribution parameter used in that analytical expression and (iii) a graphical user interface that could make easy to work with the resulting software. There is a lot of work to be done before this objective is reached by the present authors, but there are some computer programs (in fact joining these codes must be a part of the future developments of the present work) written and being tested by them. The current status of this project and its intended future developments are presented in the remaining of this paper.

2. Heat flux distribution parameter estimation

The first thing needed to allow the heat flux distribution parameter estimation is an adequate definition of that parameter. The definition used in the present work comes from the circular gaussian model to the heat flux distribution given by

$$q''(x,y,t) = \frac{\eta IU}{2\pi\sigma^2} \exp\left[-\frac{(x-vt)^2 + y^2}{2\sigma^2}\right] \tag{1}$$

where q'' [W/m2] is the heat flux; x [m] is the welding direction and y [m] is the coordinate perpendicular to it, both being inside the plate surface plane, as shown in Figure 1 for a plate with a finite thickness H [m]; t [s] is the time; v [m/s] is the welding speed; I [A] the welding current; U [V] the difference of electric potential across the arc; η [nondimensional] the arc thermal efficiency and σ [m] is the heat flux distribution parameter that we want to estimate. This kind of model is used for some different welding processes, but it is particularized here for arc welding, in which the product η IU represents the total heat (in watts) entering the plate.

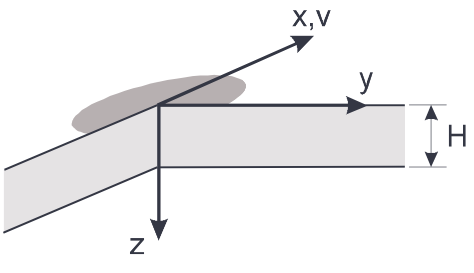

Figure 1. Coordinates system over a plate of finite thickness *H*, the welding speed *v* is also indicated

For the explanation that follows it does not matter how exactly is computed the peak temperatures field through the plate. This will generally involve the use of a numerical procedure for maximum search: in Santos (2001) and Santos *et al.* (1999) the use of the Brent's algorithm is reported. More important than this is to note that here is assumed a linear dependence between the peak temperatures and the welding thermal efficiency (that is generally not valid when thermal properties vary with temperature). Then our equation for computing the peak temperature at a given point (x,y,z) inside the plate will be represented by

$$T_{\text{peak}}(x,y,z) = \eta\,\Theta(x,y,z,v,\sigma,I,U,k,\alpha,\ldots) \tag{2}$$

where k [W/(m·K)] is the thermal conductivity of the plate material, α [m^2/s] is the thermal diffusivity and the ellipsis is representing other parameters possibly used, as the plate thickness, the convection and radiation heat transfer coefficients through the plate surfaces and so on. In the remaining of this paper parameters that are held constant during the heat flux distribution parameter estimation will be omitted and, accordingly, for a given cross section of the weld, Eq. (2) could be rewritten as $T_{\text{peak}}(y,z) = \eta\,\Theta(y,z,\sigma)$.

Knowing the peak temperatures that were reached at two distinct points, (y_1,z_1) and (y_2,z_2), of the weld cross section and recognizing that the heat flux distribution parameter σ and the arc thermal efficiency η must have constant values, it can be written, from Eq. (2)

$$\frac{T_{\text{peak}}(y_1,z_1)}{\Theta(y_1,z_1,\sigma)} = \eta = \frac{T_{\text{peak}}(y_2,z_2)}{\Theta(y_2,z_2,\sigma)} \tag{3}$$

that can be put in the more standard form,

$$\frac{T_{\text{peak}}(y_1,z_1)\,\Theta(y_2,z_2,\sigma)}{T_{\text{peak}}(y_2,z_2)\,\Theta(y_1,z_1,\sigma)} - 1 = 0 \tag{4}$$

and solved for the heat flux distribution parameter σ, using a method for nonlinear equation solution. In the present work the secant method (see, *e. g.*, Gerald and Wheatley, 1989, sec. 1.3) was adopted. Having calculated the heat flux distribution parameter σ, it is easy to calculate the arc thermal efficiency η using Eq. (3). Presently the graphical user interface request the user to locate two points (y_1,z_1) and (y_2,z_2) pertaining to an isotherm (of peak temperature), and take specifically the points identifying the width of the region delimited by this line and the depth of this region, so (y_1=width/2, z_1=0) and (y_2=0, z_2=depth).

3. Graphical user interface

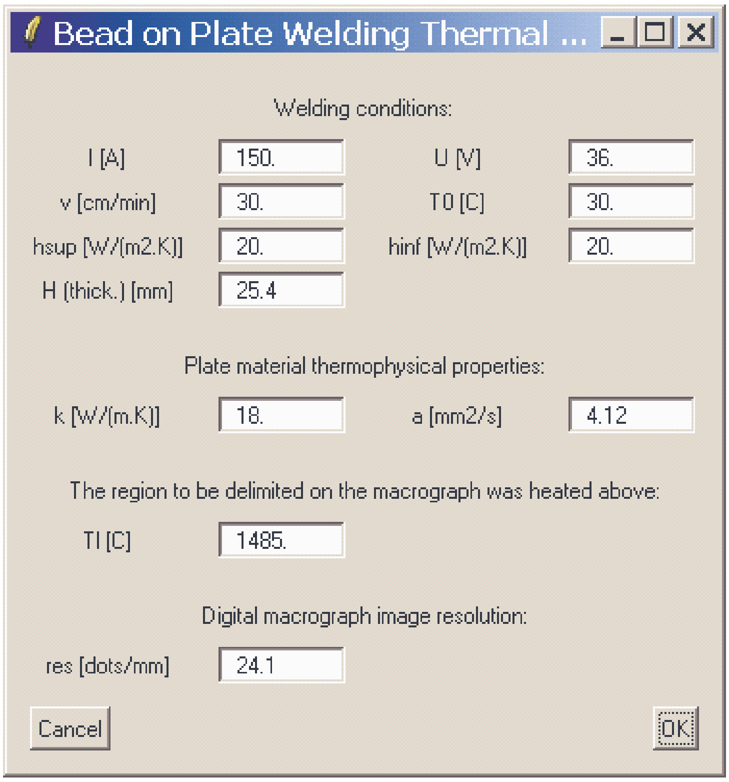

Figure 2. Start form, used for input information related to the welding conditions, material properties and macrograph resolution

When the program is started, the first window opened is that shown in Fig. 2. It is used for the input of the welding conditions (arc current *I* [A], arc voltage *U* [V], welding speed *v* [cm/min], initial plate temperature, assumed as being equal the environment temperature, T_0 [°C], convection/radiation heat transfer coefficients h_{inf} and h_{sup} [W/(m^2·K)] and the plate thickness *H* [mm]), the plate material thermal properties (thermal conductivity *k* [W/(m·K)] and thermal diffusivity α [mm^2/s]), the temperature corresponding to the start of the transformation to which the region that will have its geometry identified on the macrograph was subject (T_l [°C], in the examples shown below, the chosen transformation was the fusion, the identified region was the weld molten zone and the temperature T_l was the melting temperature of the plate material) and the digitized macrograph resolution (that expresses how many pixels in the macrograph are being used to represent one millimeter of the weld cross section).

Many of the parameters asked for in the first windows are not readily available. The arc voltage, for example, frequently is not measured. Although the errors in the values of the welding current and/or voltage across the welding arc will influence the value estimated by the computer for the thermal efficiency, what really matters for the temperatures calculation is the total heat entering the plate, given by the product ηIU. Therefore coarse approximations to the average welding current and arc voltage can be used without major problems. Precise values of heat transfer coefficients are difficult to obtain and it would be really hard to define one average value for this coefficient valid for the entire lower plate surface, and a similar average for the upper surface (that is being heated by the arc, moreover). But, as mentioned in the introduction, for plates not too thin, most of the heat flows inside the plate being welded (that is assumed to be infinitely wide and long – an hypothesis that becomes inadequate for instants too long after the start of the welding, when all the plate is significantly hotter then it was initially) and, for this, the errors in coefficients describing the heat transfer across the plate surfaces are generally not critical for the calculation of temperatures inside the plate. Typical values, as those given in the Table 1.1 of Incropera and De Witt (1990), may be used for these heat transfer coefficients in most of the situations. Plate material thermal properties vary with temperature, and so adequate average values must be used. Even the temperature T_l taken as the temperature characteristic of a material transformation (points heated above T_l must be distinguishable, in the macrograph image, of those that did not reached it) may be not so easy to define, since many transformations occurs in a temperature range that changes according to the observed heating rates, cooling rates and/or times of residence at certain temperature levels. Although the fusion line (corresponding to the melting temperature) is usually sufficiently well defined, and therefore a good choice, in some situations, specially for obtaining thermal cycles in positions relatively far from the fusion line, another transformation temperature may be more convenient. Finally the determination of the macrograph resolution is a task that demands some care and is discussed in the next section.

When all the data asked for in the first form was input and the OK button is pressed, the window shown in the Fig. 3 pops up (without the yellow lines, that will be explained in the next paragraph).

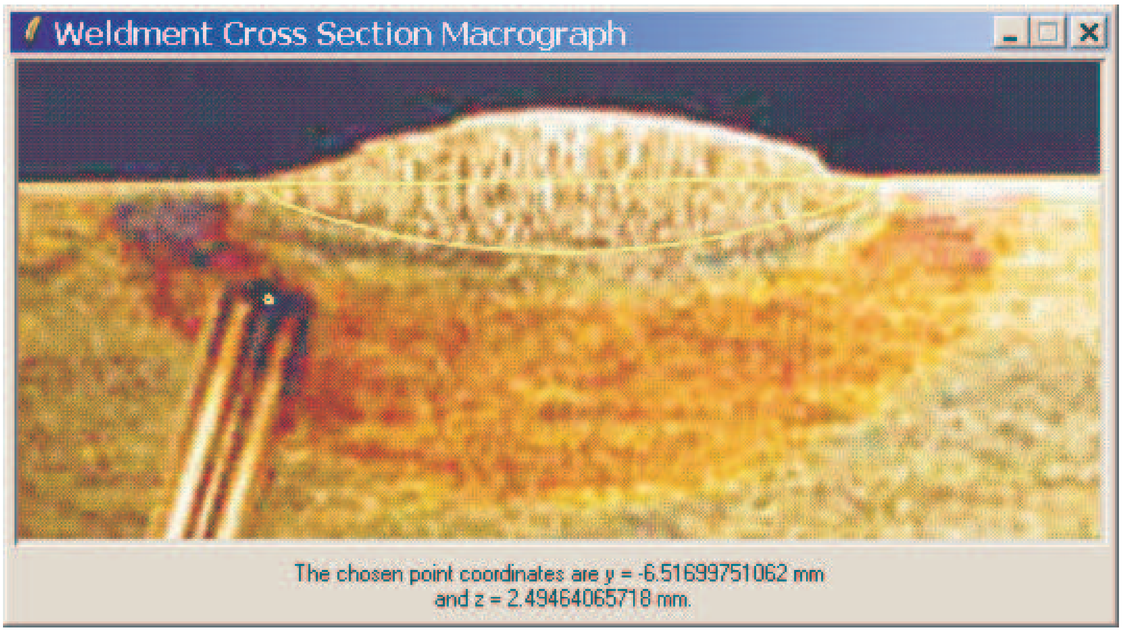

Figure 3. Digitised macrograph window

The most important part of the graphical user interface here discussed is represented in the Fig.3. In the window shown there the user can input geometrical data regarding a visible transformed weld region while looking to the weld cross section image and visualizing the data being input. When the windows first appear there is just the macrograph image. In the bottom border of the window the user is asked for clicking with the mouse over two points on the plate upper surface. These two points are used to draw a yellow straight line, like that shown in the Fig. 3, that represents the original superior surface of the plate (as it was before the plate geometry modification represented by the weld reinforcement). After the user has clicked above the two points and the horizontal line was drawn, the user is asked for clicking over a point corresponding to the depth of the region heated above T_l (the distance between this point and the previously drawn straight line is assumed to be the depth of this region) and then for clicking over other two points corresponding to the width of the same region (the perpendicular projection of these points over the straight yellow line drawn before are taken as the extremities of the region and the origin of the *y*-*z* coordinates system used to identify points over the weld cross section is placed at the middle of these extremities). When the three points to be picked by the user were chosen, a semi-ellipse is drawn having as axes half the assumed weld width and the assumed weld penetration.

After this the user is prompted for allowing the start of the numerical procedures leading to the estimation of the parameters σ and η.The user is then asked if he or she would like a better approximation of the geometry of the line delimiting the region heated above T_l . If the user answer is positive it starts a procedure calculating two more points over the line where the peak temperature is T_l, employing the recently estimated parameter values, these two points are used (in conjunction with those three already used for drawing the semi-ellipse) to draw a curved line that is not exactly elliptical, like that shown in the Fig. 3. And then, finally, the user is prompted for choosing a point, over the weld cross section, where he or she would like to know the thermal cycle to which the material was subject during welding. A small (5 pixels wide) yellow circle is drawn around that point and the user is asked for allowing the start of the numerical procedure for calculating the thermal cycle at that point using the σ and η values previously estimated and some of the data input through the window shown in Fig. 2. When this numerical procedure is finished the thermal cycle is shown as a graph, like that appearing in Fig. 4, in a Gnuplot window called by the program presented here.

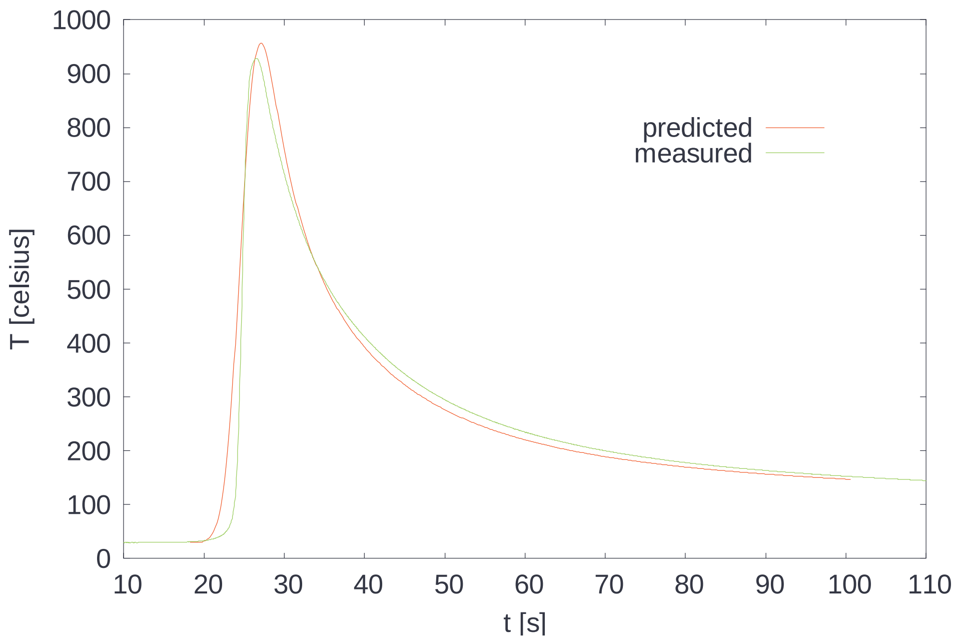

Figure 4. Thermal cycles corresponding to the yellow point at the extremity of the blind hole (drilled for placing a thermocouple) visible in the macrograph shown in the Fig. 3

The graph shown in the Gnuplot window is different from the graph in Fig. 4 mainly because of the experimental results added to that figure for supporting the discussion presented in the section 5. After examining the graph or the thermal cycle the user can choose another point where the thermal cycle should be calculated or leave the computer code, closing its windows by clicking at the X-marked button in their upper right corner.

This is not expected, but it can happen that the graphical interface stops to respond to user inputs for a too long time, after one of the numerical calculation procedures is started. The numerical calculations are performed by executable codes named “inverse” (estimates σ and η), “bettertl” (calculate additional points over the line delimiting the region heated above T_l) and “cycle” (calculates the thermal cycle at a given point of the weld cross section). When the program does not respond for too long the best remedy may be to look for processes corresponding to these executable codes, using some kind of computer task manager, and kill them (in fact only one of them should be running at a time). The “inverse” and “bettertl” codes solve nonlinear equations, and is not easy to make them fail safe.

4. Macrograph image preparation and determination of its resolution

A very common situation is to have a macrograph image, do not know how many pixels are used in it to represent 1 mm of the weld cross section, but know some dimension that can be identified in the image. In Fig. 5, for example, the plate thickness, known to be of 1 inch (25.4 mm), is clearly seen.

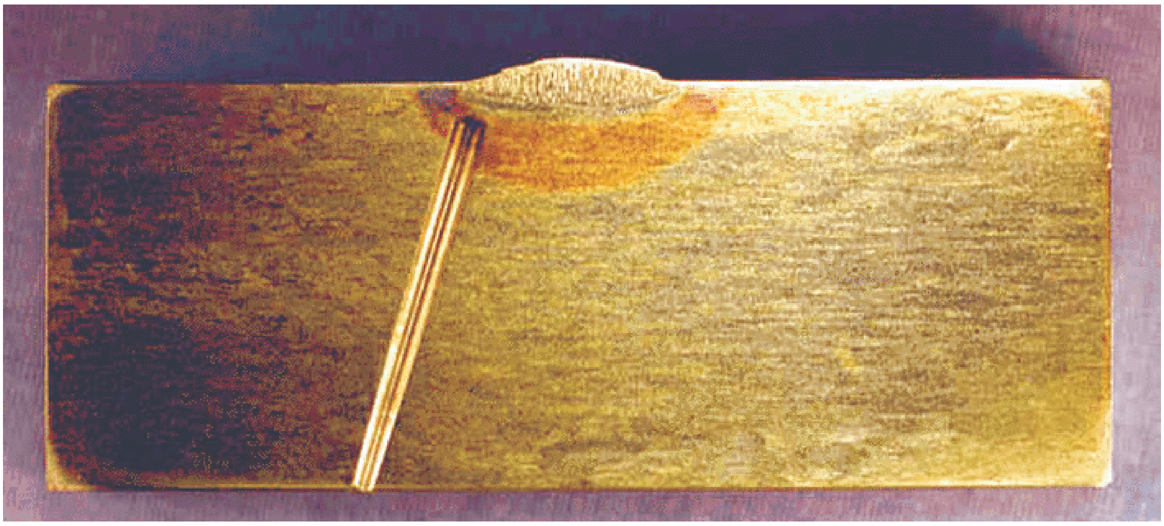

Figure 5. Original macrograph image, from which that shown in Fig. 3 was extracted

If one knows the distance in millimeters between two points identified on the weldment cross section image, all that is needed are the coordinates in pixels of these same points on the image, in order that the distance between them in pixels could be calculated and then divided by the distance in millimeters (this quotient is the desired resolution). The MS Paint shows the coordinates in pixels of the point under the cursor at the right side of its "Status bar" (that is hide or exhibited, according to what is selected by the user at the menu "View"), but early Paint versions worked only with the BMP format and even the modern versions only perform 90° image rotations, so it is not good for that task. In the Adobe Photoshop the coordinates in pixels are shown at the palette "Info" (shown when the user selects the option "Show Info" at the "Window" menu) if the user selects "pixels" as the rulers units at the menu "File" / "Preferences" / "Units & Rulers...". The same information can be obtained in other image editors, like the freeware Gimp. Even when the resolution of the macrograph image is automatically given, as occurs if it is obtained by placing the weld specimen cross section (polished and chemically attacked for revealing the transformed region) directly over the glass of a desktop scanner, it is a good idea to verify the given value using known dimensions of the specimen.

There are no image editing capabilities in the computer program developed by the present authors. All that is done by its graphical interface is to present, in a window like that depicted in the Fig. 3, the image stored (in the GIF format) in a file named "macro.gif" placed at the directory where the program is. The image appear at the computer screen resolution and for the commonly used 800×600 pixels screen configuration a image having 600×400 pixels is adequate. Therefore it is important that the user cut from the initial macrograph image a rectangle containing the region heated above T_l and the points where the thermal cycle must be calculated, but that should not be very larger than the necessary for containing this. In the cut process the image resolution does not change, but the cut image will probably have a width smaller than 450 pixels or greater than 700 pixels (its actual size can be read at the window called by selecting in the menu "Image" the option "Attributes..." in the MS Paint, in the Adobe Photoshop the corresponding window is called by selecting in the menu "Image" the option "Image Size...") and so should be stretched or shrunk to a more adequate size. In the MS Paint an integer stretching percentage can be selected at the window called by selecting the "Stretch/skew..." option at the menu "Image". The percentage to be selected (the same in the horizontal and vertical directions) is the nearest integer to the desired size by actual size ratio multiplied by 100. The resolution of the stretched image will be the original resolution multiplied by the selected percentage divided by 100. In the "Image Size" window of the Adobe Photoshop (the same used to verify the image size in pixels), if the option "Resample Image" is checked, the user can select directly the final image size in pixels (and if the option "Constrain Proportions" is also checked the coherence between the horizontal and vertical dimensions is automatically preserved). The resolution of the resampled image is obtained by multiplying the original resolution by the new width (or height) in pixels divided by the original width (or height) in pixels.

5. Results discussion and conclusion

Figure 4 shows a good agreement between the thermal cycle predicted by the computer program described in the present work and that measured using a chromel-alumel thermocouple (type K) by Borsato (2001). The welding was done using a flux cored consumable electrode over a 1 inch (25.4 mm) plate of duplex inox steel UNS S31803 initially at 30°C. The welding current was 150 A, the arc voltage 36 V and the welding speed was 30 cm/min. For the duplex inox steel the average values of 18 W/(m·K) for the thermal conductivity and 4.12 mm^2/s for the thermal diffusivity were adopted and the melting temperature was taken as 1485°C. The heat transfer coefficients through the plate surfaces were estimated as 20 $W/(m^2·K)$, and the resolution of the macrograph image shown in Fig. 3 is of 24.1 pixels/mm.

Figure 6 shows an image analogous to that shown in Fig. 3, but for an autogenous TIG weld done over a 10 mm plate of carbon steel AISI 1020 initially at 19.5°C, using a 100 A welding current. The average arc voltage was 10.1 V and the welding speed 10 cm/min. For this low carbon steel the average thermal conductivity was taken as 40 W/(m·K), the thermal diffusivity as 8 mm^2/s and the melting temperature as 1520°C. The heat transfer coefficients through the plate surfaces were estimated as 10 $W/(m^2·K)$, and the resolution of the macrograph image shown in Fig. 6 is of 94.7 pixels/mm.

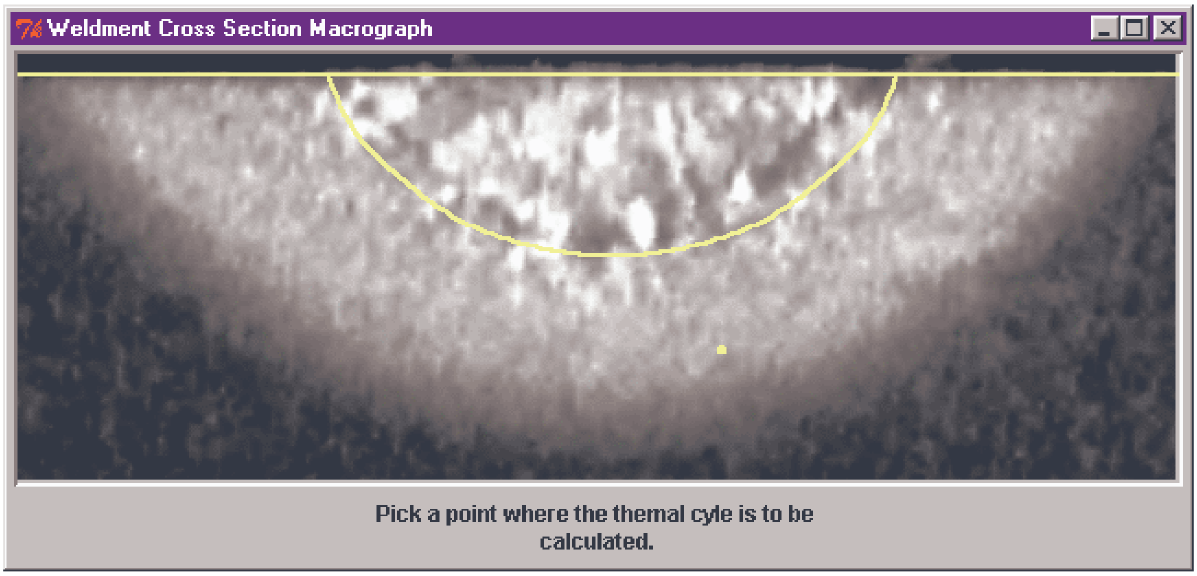

Figure 6. Digitised macrograph of an autogenous TIG weld done over an AISI 1020 steel plate

Figure 7 shows a comparison between the results predicted by the computer program described in the present work and that measured using a chromel-alumel thermocouple (type K) by Santos (2001). The good agreement again observed is not surprising. This computer program is based in a mathematical model adequate for these bead on plate welds were the hydrodynamics of the weld pool do not play a major role. The observed differences between theoretically predicted and measured temperatures were expected and are partially explained in Santos (2001) and Santos *et al.* (2000b). So, the authors conclusion is that their work is not going in a wrong direction. The theory in which the present computer program is based would not allow the modeling of a very wide class of welds, but when tested in situations compatible with that theory, the program worked nicely and showed that it can becomes a very powerful tool for welding metallurgy research an teaching.

This computer program certainly can be made better, more easy to use and able to cope with some situations for which the numerical procedures are already developed, but the graphical user interface is not yet (full penetration weld represents the most interesting of those situations). The present authors will try to continue the development of this work, but the source codes of the program, in its current status, are already available, for free, by request to the first author. Tk/Tcl script language interpreters and the Gnuplot, needed by the graphical user interface, are freely available at the internet, as also is the G77 compiler used with the Fortran 77 code of the numerical procedures.

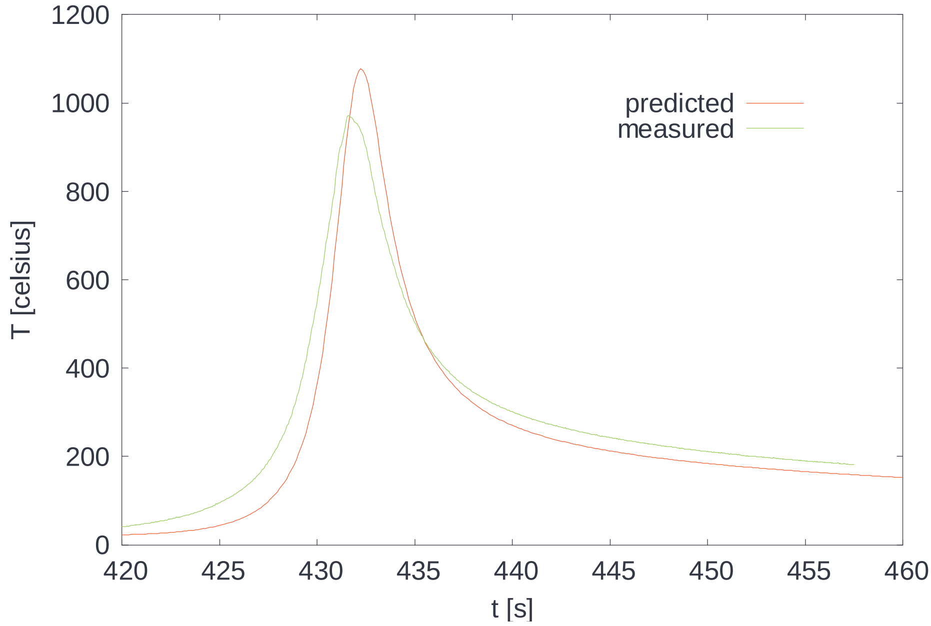

Figure 7. Comparison of predicted and measured thermal cycles for an autogenous TIG weld realized over an AISI 1020 steel plate

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5. Responsibility notice

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