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PREDICTING TEMPERATURE PROFILE AND TEMPERATURE HISTORY FOR VARIED PARAMETERS OF A WELDING PROCESS USING ROSENTHAL'S APPROACH FOR SEMI-INFINITE SOLID

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ABSTRACT

Temperature profile and history can be used to characterize a welding process. This paper applied Rosenthal's thermal solution of a moving heat source over infinite solid to grab ideas how parameters involved in the welding process affect temperature profile and temperature history of selected nodes. Based on parametric study, it can be concluded that higher thermal conductivity caused shallow penetration since the embedded heat tend to spread out to the cooler region. To obtain equal penetration the power should be increased, but this caused the faster cooling rate. Increasing the welding speed has equal influence with elevating the specific heat that causes narrower isothermal lines although their length insignificantly altered.

Keywords: ttemperature profile, temperature history, rosenthal's approach, parametric study.

INTRODUCTION

Before welding is applied the best parameters should be defined in the Welding Procedure Specification (WPS). Determining the best welding parameters through experiment work blindly is energy and time consuming which leads to economical cost. The most popular method which is recently used to predict the best parameters for the welding process is Finite Element Method (FEM). But using FEM needs an accurate program which is sometime difficult to be accomplished. Another simpler method is using an available analytic solution which is tried to be applied in this article.

The important aspects that can be used to characterize the welding process are isothermal profile and temperature history. It should be noted that in this paper the isothermal profile indicates temperature distribution at a certain time while the temperature history represents instantaneous temperature of a certain point in the welded material. Other resulted properties usually can be correlated to the temperature history and isothermal profile.

This paper demonstrates analytic approach using Rosenthal's equation to describe temperature history and isothermal profile of a welded plate. The temperature histories and temperature profile depend on the welding parameters. These parameters was taken from previous experiment.

The weld pool shape and cooling rate for varied transverse position were evaluated. The captured data may be used as a tentative data to limit the number of experiments to determine best parameters in the WPS.

RESEARCH PROCEDURES

Rosenthal [1] developed pseudo steady state condition solutions for moving heat source over semi-infinite solid. The Rosenthal's approach provides temperature of a certain position relative to a point heat source. A few modification and interpretation of the equation were taken and constituted as mathematical expressions to describe temperature distribution in the welded material and temperature history of evaluated nodes. These mathematical expression then converted into a MATLAB subroutine to produce graphs of temperature distribution and temperature history for certain welding parameters. By changing constants which represent parameters of a welding process in the MATLAB subroutine, a parametric study can be carried out.

THE ROSENTHAL's SOLUTION

A welding process is sketched as shown in Figure-1 which is consisted of fixed coordinate system (x, y, z) and moving coordinate system (ξ, y', z'). If the welding torch have travelled for enough distance from start point the temperature profile which considered from moving coordinate system is in pseudo steady state condition (sometime also called as quasi steady state). Observing the weld pool shape of a welded plate, Rosenthal developed an analytic solution for temperature distribution of welding process over semi-infinite solid which is expressed as in equation (1).

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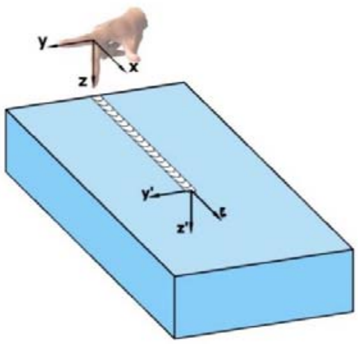

Figure-1. Fixed and moving coordinate systems.

$$\Delta T = \exp\{-v\xi/(2\alpha)\cdot f(\xi, y', z')\} \quad (1)$$

where v is welding speed and α is thermal diffusivity of welded materials. The thermal diffusivity α may also expressed as $\lambda/\rho c_p$ with λ, ρ and c_p represent thermal conductivity, density and thermal specific heat respectively. Semi-infinite solid can be represented by welding of a very thick base material. Equation (1) consists of a asymmetric function: $exp\{-v\xi/2\alpha\}$ and symmetric function: $f(\xi,y',z')$. The asymmetric function is found along the direction parallel to ξ and the symmetric function is along lines that are parallel to y and parallel to z. If the welding speed equals to zero, the asymmetric function will be a unity and only the symmetric function is left. Zero welding speed means a case of heat liberated by a stationary point which is much easier to obtain a solution for than the moving point heat source. A final solution proposed by Rosenthal for the moving point heat source on a semi-infinite solid is expressed in equation (2) where R is the distance from the heat source. T_0 is added to account for the initial temperature of the welded plate. The symmetric function of equation (2) is $\frac{\dot{q}}{2\pi\lambda R}\exp\{-vR/2\alpha\}$ with $\dot{q}$ express heat rate embedded to the welded material. In the real welding process the heat rate can be expressed as ηEI where η is the welding efficiency, E is voltage and I is current.

$$T = T_0 + \frac{\dot{q}}{2\pi\lambda R}\exp\{-v(\xi + R)/(2\alpha)\} \quad (2)$$

For varied (ξ, y', z') positions the pseudo steady state temperature can be obtained using equation (2). If the welding is started at (x_o, y_o, z_o) and a temperature history is considered for a point at (x, y, z), the instantaneous relative position from welding center can be obtained by: $\xi = (x - x_o) - vt$, $y' = (y - y_o)$ and $z' = (z - z_o)$. The instantaneous temperature then can be solved by substituting the instantaneous relative position to equation (2). Temperature histories for certain position then can be constructed using varied time t.

RESULTS AND DISCUSSIONS

First temperature distribution and temperature histories for a typical welding condition was made. As seen in equation (2) the important parameter are embedded heat rate, thermal conductivity and diffusivity of base material, and welding speed. Those parameters which were taken from previous published papers [2-5] are: $\dot{q}$ = 2 kW, λ = 45 W/m °C, α = 13.028 cm^2/s and welding speed v = 5mm/s. Inputting those parameters into the MATLAB subroutine yield temperature profile as shown in Figure-2. From Figure-2 as it was expected the temperature profiles are symmetric in the y'z' plane and are not in the two other perpendicular planes. Also it can be concluded that the temperature are equally distributed in the y' and z' directions. It is not surprising since from equation (2) the effect of y' and z' alters the distance R with equal influences. It should be noted that this condition is not accomplished in the plate welding since the limited plate thickness. The thicker the plate the closer equation (2) predicts the temperature profile of a real welding.

Figure-2 also demonstrated a phenomenon that the isothermal line is "dragged" to the rear as the effect of welding speed. How the welding speed affects the isothermal line will be discussed latter. The weld pool shape can be described by 1400 °C isothermal line (1400 °C is a melting temperature of typical steels).

Temperature histories at top surface for varied transverse distance from weld center line are shown in Figure-3. It should be noted that varied through thickness distances for this approaches also have equal effect as it has been demonstrated in Figure-2. As it is found in the welding practice, the peak temperature is lower with further distance from the weld center line. Another important aspect is the peak temperature takes place later for the further distance. This lagging effect can be explain as follow: first as shown in Figure-3, the peak temperature of a point at weld center line was considered takes place at t = 0s. Since peak temperature of the point at weld center

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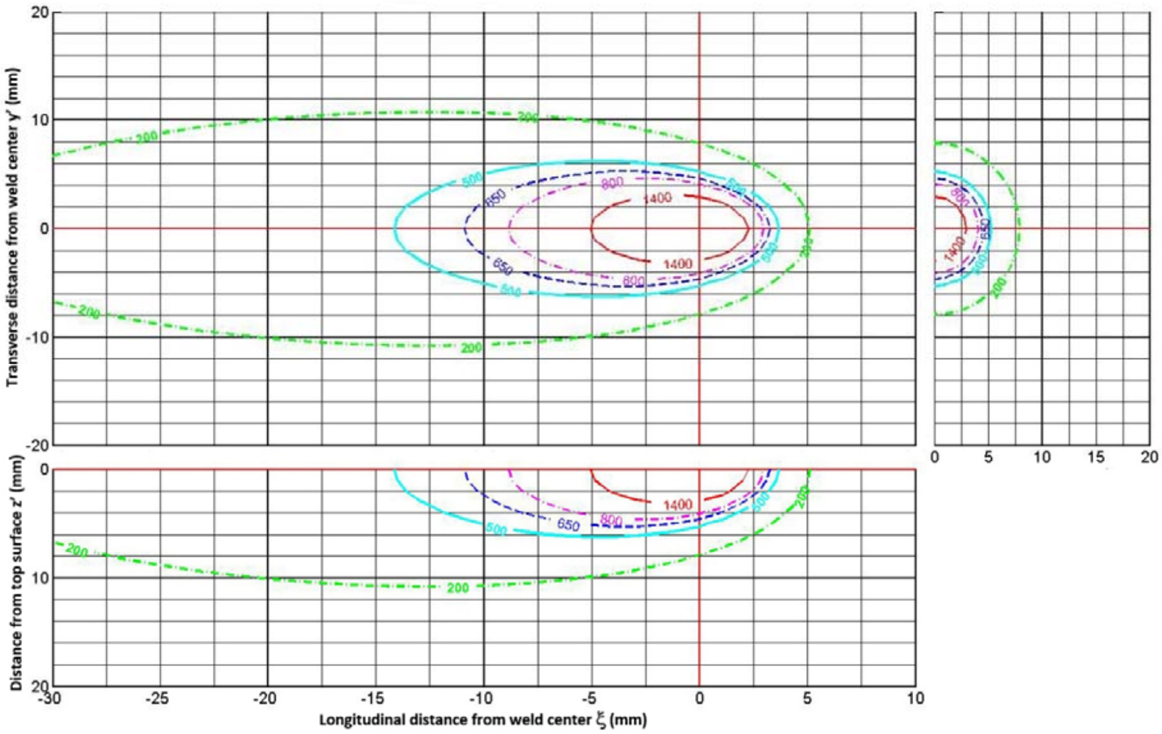

Figure-2. Temperature profiles for typical parameters.

line is achieved when the heat source is exactly at the point, this point has the highest temperature and heat is transferred to the surrounding. For higher distance from the heat source the longer time is needed to transfer the heat hence the peak temperature take place later for the higher y' values. Another important aspect that can be resumed from Figure 3 is the cooling rate. The cooling rate determines the final microstructure configuration and residual stress (5). Figure-3 shows the cooling rate is higher for the closer position to the weld line. This phenomenon is confirmed by the higher percentage of martensite in the HAZ for the closer position to the weld line in the application of welding process to ferritic steels (5).

Parametric study can also be applied to the developed MATLAB subroutine. As can be seen in Figure-2, temperature profile of top surface abled to give a general insight of temperature profile from two others perpendicular surfaces. Figure-4 shows the effect of increased thermal conductivity, welding speed and thermal diffusivity respectively to the temperature profile on the top surface.

Comparing Figures-4a and 4b can be said that the increased thermal conductivity yield narrower isothermal lines. The thermal conductivity in Figure-4b is twice of the initial typical parameter. For steel welding the 1400 °C isothermal line depicts the weld pool shape. In the real welding the need is the penetration which is represented by the width of 1400 °C isothermal line. Since for high thermal conductivity the heat is easily transferred to the surrounding cooler material, the 1400 °C isothermal line cover the narrower area as the effect of bigger transferred heat to the cooler area. Increased welding speed and thermal diffusivity as shown in Figures-4c and 4d show equal trend. It is not surprising since the equation (2) can be rewrote as $T = T_0 + \frac{\dot{q}}{2\pi\lambda R}\exp\{-v\rho c_p(\xi + R)/(2\lambda)\}$ which shows the contribution of welding speed v and specific heat c_p to the temperature T is equal.

The thermal conductivity and diffusivity are uncontrolled parameters which depend on the welded material whilst embedded heat rate ($\dot{q}$) and welding speed are welding process parameters which can be adjusted. It may a practical interest to observe the welding process parameters that able to provide equal penetration for materials with different thermal conductivityλ. The most plausible practice is adjusting the inputted power instead of welding speed. In Figure-5 temperature profile and temperature history are observed for the increased thermal conductivity with elevated inputted power hence the penetration is almost equal. The increased λ and $\dot{q}$ are 90 W/m °C and 3.5 kW respectively. The top Figures are temperature profile and temperature history for typical parameters whilst the bottom is for increased thermal conductivity and inputted power. It can be seen by

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increasing the power for the higher thermal conductivity of the material, the 1400 °C isothermal line has equal transverse width hence they have equal penetration.

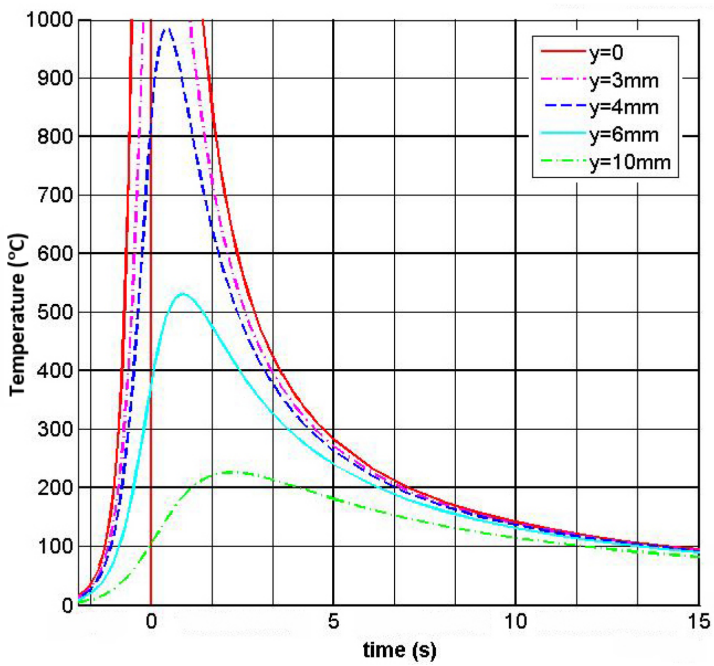

Figure-3. Temperature history of nodes with varied distance from the weld line.

Observing temperature history in the right side it can be concluded that the cooling rate is faster for the increased thermal conductivity λ and inputted power although they have equal penetration. The cooling rate usually is referred as time needed to cool from 800°C to 500°C which is usually symbolized as $t_{8/5}$. The cooling rate is resumed in Table 1 to give comprehensive ideas.

Table-1. Cooling rate.

y	Typical parameters			Increased conductivity		
	t800	t500	t8/5	t800	t500	t8/5
0	1.77s	2.83s	1.06s	1.55s	2.48s	0.93s
3mm	1.46s	2.58s	1.12s	1.33s	2.31s	0.98s
4mm	1.13s	2.36s	1.23s	1.11s	2.17s	1.06s
6mm	N/A	N/A	N/A	N/A	N/A	N/A
10mm	N/A	N/A	N/A	N/A	N/A	N/A

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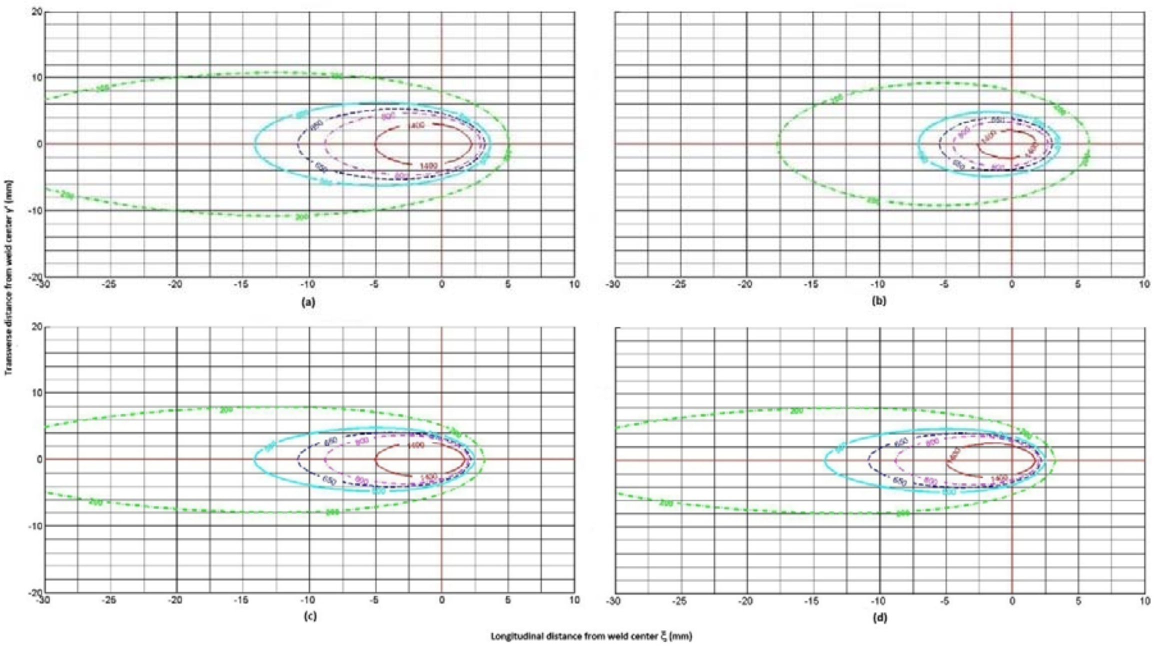

Figure-4. Temperature distribution for varied parameters (a) typical parameters, (b) increased thermal conductivity (c) increased welding speed and (d) increased thermal specific heat.

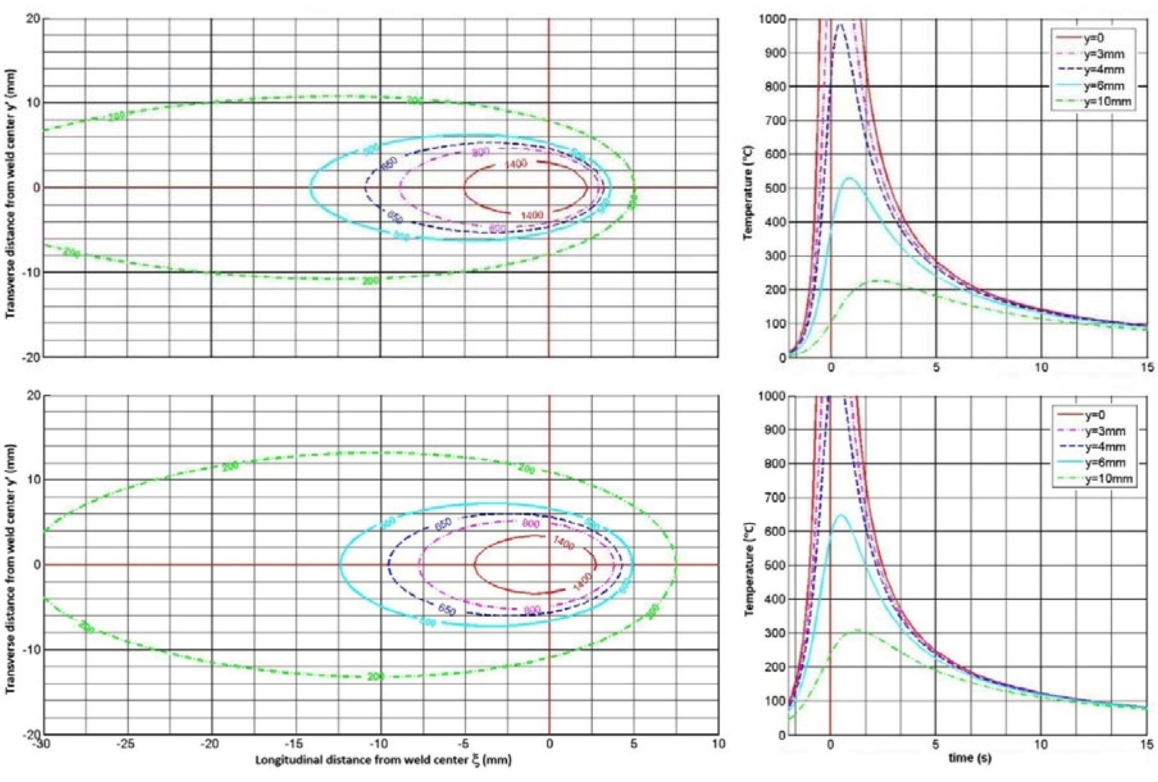

Figure-5. Temperature profile and temperature history for elevated thermal conductivity λ and increased inputted power.

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CONCLUSIONS

Composing Rosenthal's solution in the MATLAB subroutine with few modifications provides temperature profile and temperature history that can be used as early signs for best parameters in the WPS. However, it should be noted that the Rosenthal's does not take into account the effect of weld thickness. Parametric study also can be carried out through the MATLAB subroutine. Increased thermal conductivity restricts the isothermal area especially the weld pool which describes the penetration. To obtain equal penetration may be accomplished by increased inputted power, but it caused faster cooling rate which is unexpected in a welding process.

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