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N91-19013

1990

NASA/ASEE SUMMER FACULTY FELLOWSHIP PROGRAM

MARSHALL SPACE FLIGHT CENTER
THE UNIVERSITY OF ALABAMA

HEAT SINK EFFECTS IN VPPA WELDING

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Contract No.	NGT-01-002-099 The University of Alabama

Introduction

This report is a summary of work performed toward the development of a model for prediction of heat sink effects associated with the Variable Polarity Plasma Arc (VPPA) Welding Process. The long term goal of this modeling is to provide a means for assessing potential heat sink effects and, eventually, to provide indications as to changes in the welding process that could be used to compensate for these effects and maintain the desired weld quality. Heat sink effects are created due to irregularities of the geometry of the weldment itself or by the presence of heat absorbing material in contact with the weldment. Examples of such irregularities in the weldment are reinforcing ribs or flanges in the vicinity of the weld path. Sink effects due to material in contact with the surface of the weldment may be caused by the tooling and fixtures used in the welding process. The importance of a model for such heat sink effects as part of a successful scheme for the control of welding processes has been indicated in studies such as the report prepared by the Committee on Welding Controls of the National materials Advisory Board of the National Research Council [1].

The present study began during the 1989 NASA/ASEE Summer Faculty Fellowship Program. During the 1989 program, a simple lumped capacity model for heat sink effects was developed [2]. In addition to the development of a theoretical model, a brief experimental investigation was conducted to demonstrate heat sink effects and to provide an indication of the accuracy of the model. The model successfully predicted the trends in the magnitude of the heat sink effect as a function of the welding conditions, but consistently overpredicted the size of the effect. Thus, refinement of the model was indicated.

Early work during the 1990 NASA/ASEE Summer Faculty Fellowship Program involved examination of the preceding work to identify promising areas for refinement of the model. The areas selected for improvement of the model were the modeling of the heat sink itself and the modeling of the interface between it and the weldment. The refinements of the model have led to improved predictions of the location and, in some cases, the magnitude of the maximum heat sink effect, but the predictions continue to be consistently greater than the effects observed experimentally. Therefore, further improvements in the modeling of the heat sink effects are still required.

Summary of Original Model

The model developed in 1989 is based on the consideration of the heat sink material as a lumped capacity body whose temperature follows the temperature that would be observed in the weldment at the center of contact with the heat sink, if the heat sink were to absorb no energy. The required rate of energy absorption by the heat sink material in order to follow this temperature variation is then used as the strength of an ideal line heat sink of variable strength located at the center of the contact area.

The undisturbed temperature distribution created during the welding process is approximated by use of an analytic solution for the two-dimensional quasi-steady temperature distribution created by a moving line source of constant strength per unit length published by Rosenthal in 1946 [3]. The temperature distribution is quasi-steady with respect to a translating coordinate system with heat source fixed to the z-axis and is given by

$$T-T_{\infty}=\frac{Q}{2\pi k}e^{-\left(\frac{Vx}{2\alpha}\right)}K_0\left(\frac{Vr}{2\alpha}\right)$$

where Q is the power input per unit depth of weld, k is the thermal conductivity of the weldment, V is the source velocity in the x-direction, α is the thermal diffusivity of the weldment, x and r are the x distance and the radius, respectively, to the position of interest relative to the source, and K_0 is the modified Bessel function of the second kind of order 0. This two-dimensional temperature distribution is inadequate for calculation of temperatures in the vicinity of the weld pool itself, but provides a good, simple approximation for the temperatures away from the weld zone where heat sink material would typically be located. Thus, this expression was kept as a fundamental part of the revised model.

With the local temperature evolution at the heat sink provided by the above expression, the strength of the heat sink is calculated as the instantaneous change in temperature multiplied by the mass and specific heat of the heat sink. In order to evaluate the cumulative effect of this varying and moving (with respect to the translating coordinate system) heat sink, the expression provided by Carslaw and Jaeger [4] for the temperature distribution created by an instantaneous line source is multiplied by the strength of the source and integrated over time to yield the following expression for the temperature at time t

$$T-T_{\infty}=\int_0^t\frac{-S(\tau)}{4\pi\alpha(t-\tau)}e^{-\frac{[(x-x')^2+(y-y')^2]}{4\alpha(t-\tau)}}d\tau$$

where $S(\tau)$ is the sink strength at time τ and (x',y') is the instantaneous location of the sink. This method of determining the net effect of a varying, moving heat sink is also used in the revised model.

Revisions to Model

The revisions to the 1989 model consist of changes in the modeling of the heat sink. The first revision deals with modeling the response of the sink to the transient temperature at the base of the sink where it is in contact with the weldment. The second revision deals with division of the heat sink into several elements when its area of contact with the weldment is large. Both revisions allow the model to more accurately predict the behavior of the heat sink if the condition at the base is known from other considerations.

The transient response of the sink to the varying temperature at the base of the sink is obviously different than the assumption used in the original model that the temperature of the whole sink is uniform and equal to the base temperature. If the evolution of the weldment temperature predicted by the Rosenthal solution is examined, it is observed that the temperature at any point in the vicinity of the weld path sees a rapid climb in temperature followed by a gradual decline as the heat source (welding torch) passes. If the height of a heat sink placed on the surface of the weldment is significant, the upper portion of the sink will not experience the same rapid increase in temperature as the lower portion. The true temperature distribution approaches that of an insulated block exposed to a specified variation in temperature on one face. Duhamel's superposition theorem may be used with the transient solution for a unit step change in temperature on one surface of the block to obtain an expression for the temperature distribution in the block as described by Özişik [5]. This expression when multiplied by the density ρ and specific heat c of the sink material and integrated over the volume v of the heat sink yields an expression for the energy contained in the heat sink as a function of time. Finally, the derivative of this expression with respect to time may be taken to obtain the equivalent strength of the sink $S(t)$ as

$$S(t)=\frac{\partial}{\partial t}\int_0^v\int_0^t \rho c T_b(\tau)\,\frac{\partial\Phi(t-\tau)}{\partial t}\,d\tau\,dv$$

where T_b is the temperature of the surface and Φ is the solution for a step change in temperature. In the calculations of the revised model, the geometry of each sink element is assumed to be a rectangular prism and a series of two ramps are used to approximate the variation of the base temperature with time so that the differentiations and integrations may be performed and the sink strength may be expressed as a function of time for specified welding parameters. This sink strength is then substituted in the expression for the temperature variation due to an instantaneous heat sink discussed in the preceding section to evaluate the effect of the heat sink element on the temperature at the weld zone.

The revision to the model of dividing sinks with large areas of contact into several elements is based on consideration of the temperature field created in the weldment during the welding process. The Rosenthal solution mentioned above indicates that the temperatures attained in the weldment drop off exponentially with distance from the weld zone. Thus, the assumption in the earlier model that a sink be considered equivalent to a single line sink located at the center of the area of contact may lead to serious errors if the area of contact extends over a distance greater than the characteristic length ($2\alpha/V$) that is seen in the Rosenthal solution. The revised model therefore divides a sink into equally-sized rectangular elements that are approximately one characteristic length on a side and treats them as separate sinks in the computations.

Results and Suggestions for Future Work

Results from the revised model have been compared to results from the original model and the brief series of experiments conducted last year. It was found that the magnitudes of the temperature effects predicted by the two models agree within 10 per cent for the input conditions corresponding to the experiments. Both models predict the overall trends in magnitude of effect, but overpredict the values observed experimentally. The revised model is clearly superior to the earlier model in that it takes into account variations in heat sink geometry, but since the geometries used in the experiments performed last year were similar, this improvement cannot be confirmed based on the experiments performed. Further refinement of the model is indicated, particularly in the modeling of the interaction of the temperature fields of the weldment and the heat sink.

In addition to further refinement of the model, other work may be suggested to advance the study of heat sink effects. Further experimentation including real-time recording of the temperatures developed in weldments with and without heat sinks would clarify the manner in which the temperature fields interact and would provide a necessary guide in the evaluation of the accuracy of modeling efforts. Another possibility is the use of comprehensive commercial computational heat transfer codes to perform "computational experiments" to obtain more insight into the problem. However, given the complexity of the heat transfer phenomena associated with the welding process, experimentation under actual welding conditions should be included in support of any such endeavor. Progress has been made in understanding heat sink effects, but more work is required to achieve the long term goal of accurate predictions of these effects.

References

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