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Extension of the double-ellipsoidal heat source model to narrow-groove and keyhole weld configurations

T.F. Flint[a,b,**], J.A. Francis[b,*], M.C. Smith[a,b], J. Balakrishnan[b]

[a] Modelling and Simulation Centre, The University of Manchester, Oxford Road, Manchester, UK
[b] School of MACE, The University of Manchester, Oxford Road, Manchester, UK

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ABSTRACT

The double-ellipsoidal heat power density model proposed by Goldak, has been widely used as the basis for modelling heat transfer in arc welding operations for more than thirty years. This approach has proved to be extremely effective for a wide range of arc welding operations. However, the application of a double-ellipsoidal heat power density distribution is less appropriate for keyhole-laser or electron-beam welding operations, or in situations where arc welding takes place within deep narrow grooves. In this paper the double-ellipsoidal distribution is extended to a double-ellipsoidal-conical heat power density model in order to accurately describe transient temperature fields for a wider range of geometries and welding processes. The new extended model was validated through comparing predicted welding thermal cycles with those measured for a single pass electron beam weld, as well as those measured in a multi-pass narrow groove gas-tungsten-arc weld. In both cases, excellent agreement was obtained between predicted and measured thermal transients.

1. Introduction

Fusion welding is the most common method for assembling large metallic structures. Fusion welding involves the use of a concentrated heat source to bring about localised melting in order to join components. This localised heating leads to the generation of steep temperature gradients and rapid thermal transients, which in turn lead to large variations in micro-structure and mechanical properties, and to the generation of substantial levels of residual stress.

In the case of safety-critical components, such as those that arise in nuclear, power generation, offshore and in related sectors, it is critical that residual stresses are quantified with a high level of confidence. In order for a residual stress prediction to be made, an accurate thermal history must be obtained or predicted for the component, as was discussed by Radaj (1992). Given that many safety-critical components will have complex geometries and/or processing histories, such quantification is often contingent on the application of numerical models. Goldak et al. (1984) describe how the accuracy of numerical predictions for transient thermal fields will in turn hinge on an accurate description of the welding heat source.

Rosenthal (1941) first applied Fourier's law to moving heat sources, which were represented as either point, line or plane sources of heat. This approach resulted in reasonable predictions for transient temperature fields at some distance from the heat source, but predictions were less accurate in the vicinity of the fusion zone. Subsequent developments were proposed by other researchers and these led to improved near-field predictions for conventional arc welds. Pavelic et al. (1969) made improvements by representing the welding arc as a distributed surface flux. In order to account for the effects of arc pressure and weld pool depression discussed by Friedman (1978), the heat source may be represented as a volumetric distribution.

An approach to representing welding heat sources, that was first proposed by Goldak et al. (1984), has been widely adopted by analysts over the past thirty years. Goldak and co-workers proposed a non-axisymmetric heat source distributed in three dimensions in order to better account for the depression of the weld pool surface owing to the arc pressure. One representation that was presented was based on a double-ellipsoidal heat power density distribution. However, Goldak et al. (1985) also pointed out that arbitrary functions can be utilised to define a distribution of heat flux on the surface of a weld, or a power density distribution throughout the

* Corresponding author.
** Principal corresponding author.
E-mail addresses: Thomas.Flint@manchester.ac.uk (T.F. Flint), John.Francis@manchester.ac.uk (J.A. Francis).

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volume of a weld, and that these different functional distributions may be used with increasing or decreasing success depending on the parity of the distribution with the physical reality of the welding heat source. Goldak and co-workers stressed that if one has an exact solution of the temperature-enthalpy field in the weld pool, then one need only prescribe this solution to be a Dirichlet boundary condition, and the associated flux and power density distribution is the Lagrange multiplier that enforces this exact solution. Furthermore, appropriate flux and power density distributions must exist in cases where the temperature field solution exists. The only caveat on the choice of distribution function is that the integral must be unity. The approach proposed by Goldak has proved to be extremely effective at describing the arc as a heat source in a wide variety of applications, ranging from the case of an electric arc impinging on a flat plate, but also for cases where the arc is introduced to the base of a weld groove as described by both Bibby et al. (1985) and Gery et al. (2005).

In the time since the Goldak model was first published, there has been an increase in the application of narrow-groove arc welding process variants, which generally involve the preparation of deep and narrow weld grooves for welding thick sections of material. This increase has been driven by the desire to reduce the volumes of filler material that need to be deposited, thereby reducing joint completion times. Similarly, the utilisation of keyhole welding techniques based on the laser and electron beam (EB) welding processes has also increased. The mechanisms behind the keyhole formation in electron beam welding and the instabilities that may arise within the keyhole were reviewed by Sun and Karppi (1996). It is evident that the nature of arc welding in a deep and narrow groove, or keyhole welding with either an electron beam or a laser, is a very different scenario to that of an electric arc impinging on a flat plate. Thus, with the increasing utilisation of narrow-groove and keyhole weld configurations in mind, the authors felt compelled to examine the possibility of either extending an existing approach to the representation of welding heat sources, or proposing a new approach.

We begin by describing a double-ellipsoidal-conical heat power density model for welding heat sources; in which double-conical and double-ellipsoidal heat power density distributions, of similar form to those proposed by Bibby et al. (1985) and Goldak et al. (1984) respectively, are mathematically combined to create a power density distribution that is able to represent the heat source in a wider range of welding processes than previous power density distributions. We then describe the application of this heat source model to thermal analyses for the cases of a multipass narrow groove arc weld in a 30 mm thick SA508 steel plate, and a keyhole electron beam weld in a 30 mm thick SA508 steel plate. The performance of the model is then assessed based on a comparison of predicted thermal transients with those measured using thermocouples attached to the weld test pieces. The performance of the proposed model is also compared with the predictions arising from the application of the Goldak heat source model, as implemented with a double-ellipsoidal heat power density distribution.

2. Double-ellipsoidal conical heat source model

According to Fourier's law, heat flow is related to the transient temperature field in the domain. The temperature, $T(x, y, z, t)$, as a function of spatial co-ordinates, (x, y, z), and time, t, satisfies the heat equation at every point in the domain as shown in Eq. (1).

$$\rho c_p \frac{\partial T}{\partial t} - k\nabla^2 T = q \quad (1)$$

where ρ, c_p and k are the mass density, specific heat capacity at constant pressure and the thermal conductivity respectively; $q_{(x,y,z,t)}$ is the rate of internal heat generation which represents the heat source or sink rate in the domain. Typically $q_{(x,y,z,t)}$ has been represented by a non-axisymmetric heat source as proposed by Goldak et al. (1984), typically a double-ellipsoidal heat power density distribution, for the case of arc welding, and by a three dimensional conical distribution for beam welding processes and plasma arc welding.

The double-ellipsoidal heat source has been shown to accurately represent the heat power density from an electric arc traversing across the surface of a flat plate. However, in cases where the weld configuration deviates significantly from an arc impinging on a flat plate, this distribution should be modified in order to account for heat transfer by convection and radiation to the walls of deep and narrow grooves. In the gas-tungsten arc welding (GTAW) process, for example, the gas shielding enables significant quantities of heat to be transported to the walls of the groove by forced convection and, as there is no fusible flux concealing the arc, by radiation transfer.

Consider a gas-tungsten electric arc traversing across the surface of a flat plate. For given welding conditions, there will be a distance, perpendicular to the welding line, over which the heat flux will decay to a fraction (say 5%) of its peak value. If the same gas-tungsten arc were now transposed to the base of a narrow groove this distance would necessarily change, since some portion of the arc energy would now be transferred directly to material located above the base of the groove, through mechanisms such as radiation and forced convection. Clearly such transfer would not occur in the case of a flat plate as no material would be located to either side of the electric arc. This heat decay as a function of distance from the weld line must then be related to the geometry of the groove.

In the proposed model, below the base of the groove the power density obeys the verified double-ellipsoidal distribution proposed by Goldak and decreases to a given fraction of the peak power in a Gaussian manner in three dimensions. Above the base of the groove, the distance over which the power density decreases by a given fraction is related to the bevel angle applicable to the wall of the groove. Therefore, above the base of the groove, surfaces of constant power density look like conical sections with different semi-major axes fore and aft of the arc location. In contrast, below the base of the groove, surfaces of constant power density lie on double-ellipsoids with different semi-major axes fore and aft of the arc location. These surfaces of constant power density are shown, for cases of an arc and electron beam weld, in Fig. 1a and b respectively.

For an electron beam incident on a flat surface the heat flux distribution is analogous to that of an arc at the base of a narrow groove. The focusing of the electron beam results in a Gaussian distribution of electron energies incident upon the domain surface. These electrons rapidly transfer their kinetic energy to the work-piece via scattering interactions, and toward the centre of the beam the electron energies may be sufficient to vaporise the base material. The resulting vapour pressure can displace molten metal, enabling subsequent electrons to travel further into the material. Toward the periphery of the beam, electrons will tend to have lower energies, and fewer collisions will be required in order for their energy to be transferred to the work-piece. Therefore, as the beam penetrates the domain, the effective radius of the Gaussian energy distribution decreases as the kinetic energy of the electrons therein is converted to thermal energy. There will also be some transfer of energy from the beam axis toward the beam periphery and, as such, the electron energies on the beam axis will gradually decay with increasing depth of penetration. This gradual decay in electron energies will determine the penetration depth since, at some point, the electron energies will no longer be sufficient to cause vaporisation of the molten metal. At this position on the beam axis, the heat ought to be deposited to the work-piece in a Gaussian manner from the end point of the beam in the domain. Therefore, above this position on the beam axis, surfaces of constant power density again