On determining the shape of weld pools

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Abstract. The equations governing heat and fluid flow in weld pools for the TIG fusion welding process are presented and this coupled system is solved numerically using finite differences. Electromagnetic forcing terms, buoyancy forces, shear forces on the pool surface due to the variation in surface tension with temperature and an additional uniform magnetic field applied normal to the workpiece are all included in our model and results are displayed indicating the relative importance of these four mechanisms.

1. Introduction

Until comparatively recently little was known about the physical and chemical processes involved in welding and satisfactory welds were only produced by skilled practitioners using 'rule of thumb' techniques based on experience. Since the modern trend is towards the use of automatic welding procedures, there has been considerable effort expended in recent years in trying to understand more fully the underlying physical mechanisms.

In this paper attention is concentrated on a commonly-used fusion welding process known as TIG (Tungsten electrode with an Inert Gas shroud). In the TIG process a high current electric arc is moved along the line of contact between the two components to be joined. Sufficient heat is deposited on the surface of the materials by the arc to cause the components to melt. Then, as the arc moves away, the molten material solidifies and the components are fused together.

The first significant mathematical attempt to model the fusion welding process was made by Rosenthal [1], who derived a number of solutions of the steady state heat conduction equation $\kappa \nabla^2 T = \mathbf{v} \cdot \nabla T$, where $\kappa$ is the thermal diffusivity of the material, $T$ is the temperature at any point inside the material and $\mathbf{v}$ is the velocity of the arc relative to the workpiece. Rosenthal's model has proved popular with metallurgists for it reveals, for instance, the characteristic tail of the weld pool behind the heat source and it can also be relatively easily adapted to take account of different geometrical arrangements, distributed heat sources, varying thermal properties of the material and so on (see [2]). The model does, however, neglect fluid motion in the weld pool, and the existence of such motion has been confirmed experimentally [3,4].
In the TIG process the electrode is non-consumable and the major reasons for convection in the pool seem to be:

(a) electromagnetic body forces inside the weld pool,
(b) buoyancy effects inside the pool
and
(c) shear forces on the free surface of the pool due to both
   (i) the gas jet and (ii) the variation in surface tension with temperature
   (the Marangoni effect).

Until the last few years only (a) has received much attention. Some experiments were performed with liquid mercury [5], which could be forced to flow in different directions according to how electric current entered or left the pool. A little later the first theoretical attacks on the effects of (a) were made [6–8], by considering the flow of an electrically conducting fluid in a semi-infinite region when the current in the fluid diverged from a stationary point source on its surface. The flow induced by a similar current source on the surface of fluid confined to a hemispherical container was investigated in [9]. Unfortunately, the solutions in [6–9] all suffered from the inherent weakness that the velocity field became non-physical on the axis of symmetry for the values of the applied current typically used in welding. Replacing the point source of current by a distributed one improved the situation and, after initial work on the linear problem (valid at low currents) in [10], Atthey [11] used a distributed source model in solving the nonlinear problem in a hemispherical weld pool in a plate at realistic currents by numerical finite difference methods.

At this stage in the theoretical development of the area, therefore, there existed the two separate, but incomplete, approaches – Rosenthal's solution of the heat conduction equation for a moving heat source but a stagnant pool and, secondly, the solutions in [6–11] (and other related ones, mainly by Sozou and his co-workers) for the flow of electrically conducting fluids, created by stationary current sources, in regions of simple predetermined shape with thermal effects ignored.

Within the past few years attention has turned inevitably to combining the fluid and heat flow effects. The shape of the solid/liquid boundary in a semi-infinite material has been determined in [12,13] by finding a numerical solution to the coupled fluid and heat flow equations, but only the electromagnetic forcing terms (effects (a)) were included. The results in [12,13] revealed that at realistic welding currents the electromagnetic forces produced by a stationary, axisymmetric, distributed current source were sufficiently large to have a significant influence on the position of the solid/liquid interface. The shape of this boundary was found to be particularly sensitive to the magnitude and concentration of the applied current source.

Quite independently of the above work, investigations of a similar type were being carried out at M.I.T. and results for the development of the shape of the solid/liquid boundary with time and for the associated motion in the molten metal due to an applied, stationary, axisymmetric, distributed source