An Investigation of the Interaction of a Molten Droplet with a Liquid Weld Pool Surface: A Computational and Experimental Approach

The model shows droplet transfer strongly influences the flow pattern within the gas metal arc weld pool

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ABSTRACT. A finite element fluid dynamics model that incorporates nonlinear temperature and compositionally dependant material properties has been used to study the flow patterns generated by the interaction of molten metal droplets with a weld pool surface. The effects of single and successive droplet transfer, droplet composition, temperature, velocity, size and transfer rate have been investigated.

The model shows droplet transfer strongly influences the flow pattern within the weld pool. At low transfer rates, typical of low welding current (100 A), the relative surface tensions of the pool and the droplet influence the fluid flow within the weld pool, whereas at higher transfer rates, typical of medium current (200 A), the flow is dominated by the momentum of the impacting droplet.

Experimental determination of weld pool geometries for bead-on-plate welds, at different current levels, on plates selectively doped with sulfur, have provided some support for the model predictions.

This work demonstrates that droplet-induced convective flow should be included when modeling the weld pool behavior in GMAW.

Introduction

The properties of a gas metal arc (GMA) weld are controlled by a complex interaction of many process parameters. Many of these parameters directly affect the thermal cycle generated during welding and, through this, influence the geometry, microstructure and mechanical properties of the final weld, as well as contributing to the generation of post-weld distortion and residual stress. Significant efforts have been made to develop simulative welding models that can predict such process outcomes without the need for costly preproduction trials or experimentation.

Early attempts (Ref. 1) to calculate the thermal cycle for a given weld involved an analytic solution for heat conduction within a plate, assuming the weld could be represented as a simple point or line heat source. Contemporary, numerical conduction models generally use finite element methods of solution, with the welding arc represented as a complex distributed heat source (Ref. 2). However, there are significant limitations in this approach, which ignores or only crudely compensates for the convective transfer of heat by fluid movement within the weld pool. Convection and flow within the weld pool have a significant influence on near-weld thermal cycles and weld pool shape. They can also influence the uniformity of composition in the pool and affect the solidification behavior and the presence of defects and inclusions (Ref. 3). Hence, in recent years there has been a realization that to create a predictive model of the welding process, it is necessary to model the flow within the molten weld pool and directly include convective heat transfer (Refs. 4–19).

To date most investigations of fluid flow within weld pools have concentrated on gas tungsten arc (GTA) or laser welding processes, without including the complexities of metal transfer across the plasma. Flow in the GTA weld pool is driven by electromagnetic, buoyancy, arc pressure and surface tension forces. In welding processes, such as GMAW, that involve metal transfer across the arc plasma, the interaction of the molten droplets with the weld pool surface will be an additional important means of generating flow within the pool. It has been experimentally demonstrated (Ref. 20) the mode of metal transfer has an important influence on the pool depth and width, from which can be inferred an effect on the flow behavior.

Choo, *et al.* (Ref. 21), have investigated droplet and pool interactions with a flow visualization technique and have shown significant flow is introduced by the relative surface tension differences between the molten droplet and the pool. This result contradicts an early model (Ref. 22) of a GMA weld pool, which treated the droplets purely as heat and momentum sources, ignoring flow induced by surface interactions.

In this work, a computational model has been used to study the weld pool flow pattern induced by droplet interactions. It concentrates on examining the effect of the relative surface tension between the droplet and the pool and on the influence of droplet momentum. It is intended this work will identify some of the primary mechanisms involved in driving the weld pool flow and provide further direction for future models of welding processes involving nonautogenous metal transfer.

Computational Model

The model was developed using FIDAP (Ref. 23), a finite element, computational fluid dynamics code. The model considers a molten pool and determines the flow induced by droplets impinging onto its surface. It has been tested against the results from flow visu-

KEY WORDS

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alization experiments published by Choo, *et al.* (Ref. 21) by modeling a water/alcohol pool and droplet, and has shown good agreement in predicted flow patterns and surface velocities. Following this it has been applied to a molten steel weld pool under impact from steel droplets.

The inherent assumptions, necessary simplifications and details of the model are as follows:

1) It is considered that the droplet strikes the center of a liquid pool and that the induced flow is axisymmetric. The calculation begins with an assumed spherical droplet in contact with the flat weld pool surface. A more detailed description of the computational approach is given in Ref. 24.

This is an approximation to a droplet transferring into a developed, stationary GMA weld pool.

2) The model is taken to be isothermal. Droplet and pool were assumed to be at a constant temperature of 2700 K, as indicated by experimental measurements (Ref. 25).

Temperature gradients would normally occur within the pool and contribute to the spatial variation in surface tension and to the induced surface tension forces. However, surface tension is dependent on both composition and temperature, and spatial variation in either will induce surface forces. The process has been extensively demonstrated for GTA weld pools (Refs. 15, 26, 27). In the current work, the influence of a differential in the surface tension of the droplet and the pool has been simulated by forcing a variation in their sulfur content. Using a compositional variation, rather than simply ascribing a fixed surface tension value to droplet and pool, allows a changing surface tension as the droplet dissipates into the pool. Mathematically, the diffusion of sulfur is equivalent to temperature dissipation, but by not using temperature as an active variable, the surface tension effect is isolated from the effects of buoyancy.

It is realized the sulfur content of steel is controlled; however, in this work, it is introduced as a convenient means of adjusting the surface tensions of the droplet and the pool. Sulfur was chosen as the surface-active agent because it could be varied to form drops with higher or lower relative surface tension. In practice, it is expected the droplet would have a higher temperature than the pool and, consequently, would always have a lower surface tension.

3) The model only considers the flow induced by the droplet and its surface interaction with the pool. Arc pressure and plasma shear forces, heat flux from the arc, electromagnetic effects and buoyancy forces are not included. It is recognized all of these factors combine to influence weld pool flow, but the aim in this initial work was to isolate the relative effects of surface tension forces and momentum forces.

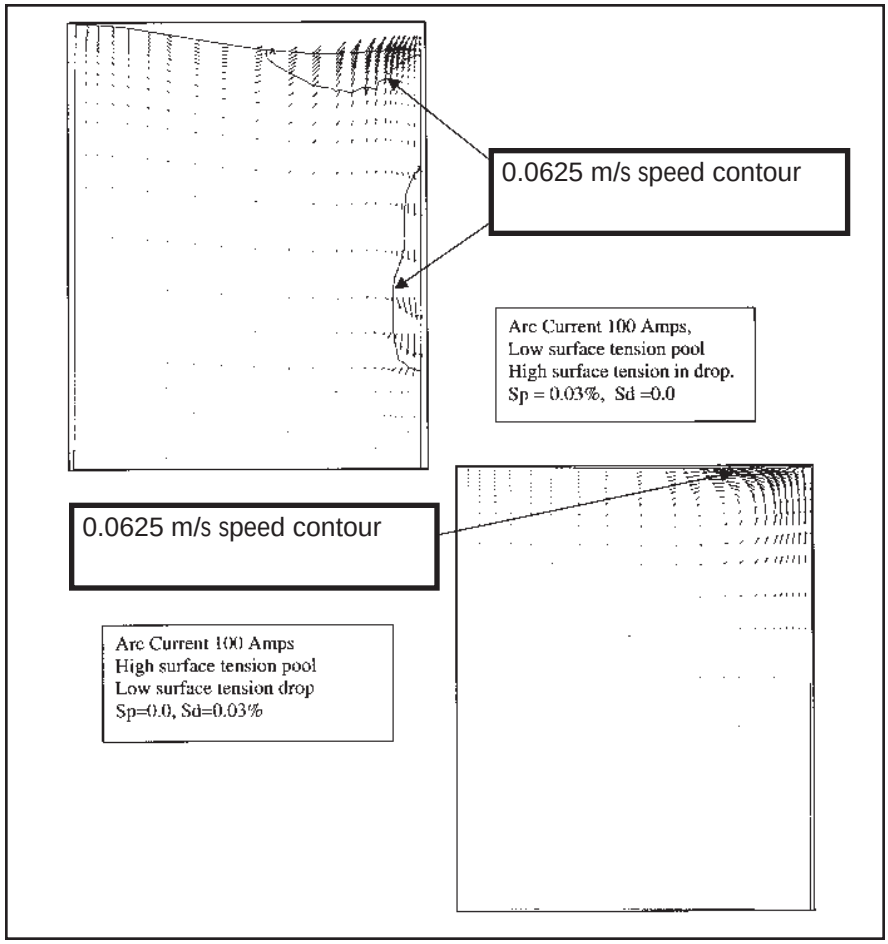

Fig. 1 — Predicted flow patterns showing flow direction and superimposed 0.0625 m/s speed contour for an arc current of 100 A. In the top view, the pool has a lower surface tension than the drop, and in the bottom view, the pool has a higher surface tension than the drop.

4) A large weld pool size of 20 mm radius by 30 mm deep was modeled. This relatively large volume was used because this is the case most sensitive to surface tension effects. In a shallow pool, an impacting drop would strike the bottom of the pool irrespective of the drop's surface tension. If surface tension gradients have a small effect on a large weld pool, they will definitely have a negligible effect on small pools. The assumed pool size also allowed direct comparison of the model with the water analog of Choo, *et al.* (Ref. 21).

5) The size, impact velocity and transfer frequency of weld droplets has been taken from previously published experimental work (Ref. 28), and these are detailed in Table 1.

6) The top surface of the pool was free to deform.

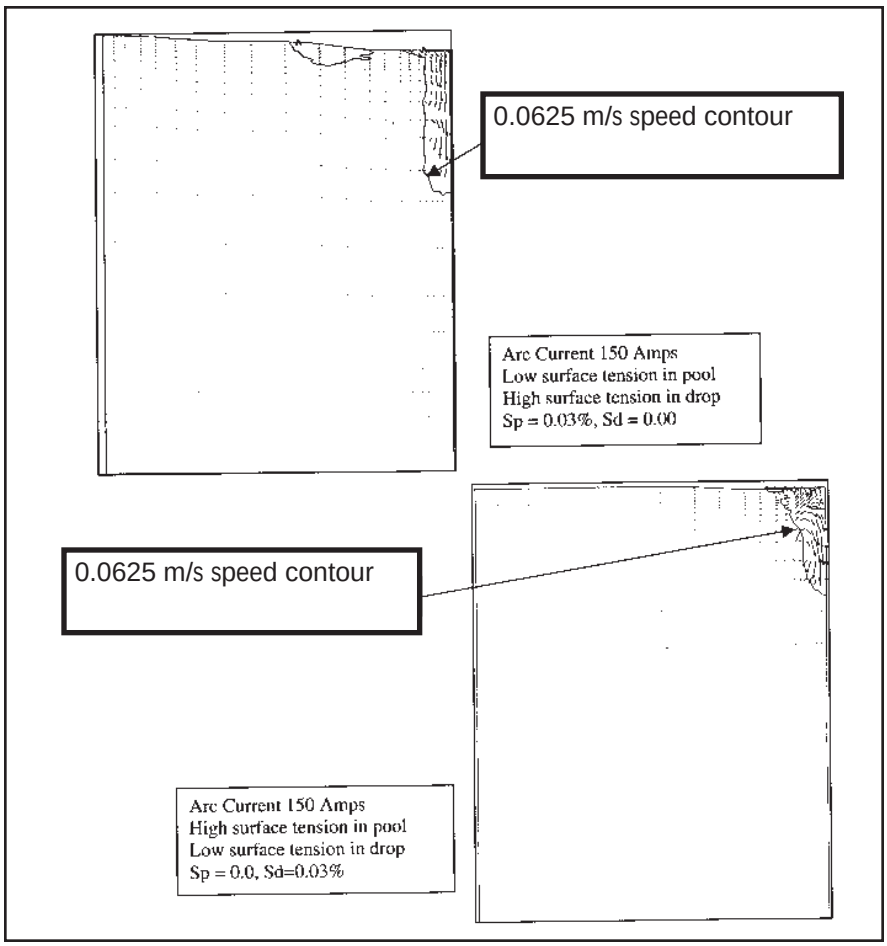

Fig. 2 — Predicted flow patterns showing flow direction and superimposed 0.0625 m/s speed contour for an arc current of 150 A. In the top view, the pool has a lower surface tension than the drop, and in the bottom view, the pool has a higher surface tension than the drop.

7) Along the edges of the pool "no-slip" conditions for a viscous fluid were assumed.

8) The flow was taken to be Newtonian. This assumption has been experimentally verified by a previous researcher (Ref. 4).

9) There is no consensus on the choice of a laminar or turbulent model; both have been questioned in the literature (Ref. 27). In this work, numerical investigations have shown a laminar model would be inappropriate at high droplet impact velocities; however, the common turbulence models are also ineffective in areas of low Reynold's number, high temperature gradients or high streamline curvature, all of which are present in the weld pool. As a compromise, the flow was considered as laminar when checking the model against the flow visualization data of Choo, *et al*. This is consistent with many previous attempts at modeling the GTA weld pool. However, when modeling the flow within a molten steel weld pool, an enhanced viscosity model was used to account for the effect of turbulent dissipation and to encourage numerical stability, as used by Choo, *et al*. (Ref. 29). At worst this approximation could lead to a 20% error in the predicted weld pool size (Ref. 27), but because the "enhanced viscosity" will have no effect on the relative magnitude of the driving forces and only influence the damping of the flow, this particular assumption should have no effect on the results of this investigation.

10) Previous work in modeling flow in GTA weld pools (Refs. 26, 27) has shown it is important to consider the effect of temperature-dependant, thermo-physical properties. In the present isothermal model, all properties were taken at a temperature of 2700 K. These values are given in Table 2.

A fundamental difficulty in any calculation of the flow within the weld pool is the lack of dynamic fluid physical properties for molten steel at high temperatures. In this study, where sulfur content has been used to change the surface tension of the pool and the droplet, the data of McNallan, *et al*. (Ref. 30), for a Fe-S binary alloy have been used. Other researchers (Refs. 15, 26) have shown this to be the best available approximation.

Numerical Experiment

Using the computational model, a series of numerical experiments was carried out. Droplets whose size and velocity were representative of three different welding currents (100, 150 and 200 A) were simulated, as indicated in Table 1.

Surface tension differences between the droplet and the pool were produced by varying their respective sulfur contents. Three different conditions were taken for each current level: a standard case where the droplet and the pool had the same composition (both 0.0% S) and two additional conditions where the droplet had a surface tension lower and higher than the pool (0.03% S in the drop and the pool, respectively).

The model was used to predict the flow pattern during successive droplet strikes, but up to 400 h of computer time was required to develop a quasi-steady state. (The computer used was a Sun Sparcstation 4/40.) Consequently, to reduce calculation time, the investigation compared effects after single droplet impacts. The flow patterns were calculated after impact from a single droplet at a time immediately prior to the next droplet strike. This approach did not compromise the results because a comparison of the flow after single and multiple droplets showed the flow induced by a single impact was characteristic of the flow induced by successive droplets. That is, if a single drop produced a radially outward flow, then the quasi-steady state produced by multiple droplet impacts was also a radially outward flow. For example, with a high surface tension drop at 200 A, the depth-to-width ratio of the 0.01 ms^{-1} speed contour was 4.23, and after 20 drops it fell to 4.11. In fact, this ratio remains approximately constant until the flow pattern is ultimately affected by the container walls. On this basis a comparison of changes in flow pattern after single droplet impacts seemed acceptable.

Results and Discussion

The flow patterns produced by the numerical model are shown in Figs. 1–3.

At a welding current of 100 A (Fig. 1), the presence of sulfur, and its effect on the surface tensions of droplet and pool, has a significant influence on the vector and speed contour plots. A droplet with a surface tension lower than the pool tends to produce a diffuse radially outward flow, with the droplet essentially spreading outward at the surface of the pool. For a droplet with higher surface tension than the pool, the flow is reversed, with the droplet producing a radially inward, penetrating flow pattern. These patterns are essentially similar to those observed and discussed by Choo, *et al*. (Ref. 26). However, at higher welding currents these effects are reduced (Fig. 2), with flow patterns becoming very similar for all surface tension conditions at a welding current of 200 A — Fig. 3. In broad terms, the droplet impact tends to produce a central downward flow within the pool. Capillary effects depend on the relative surface tensions between droplet and pool. A relatively low tension drop tends to produce flow that is radially outward, against the droplet flow. With a relatively high surface tension in the drop, the capillary effects complement the droplet flow. At higher currents the increased droplet momentum dominates the flow pattern. A comparison of the flow fields for all conditions is given in Ref. 31, but in this paper, to emphasize the difference between these results, a simple quantitative measure of the flow pattern is used. This scales the effects to the momentum-only condition when the surface tension in the droplet and weld pool are the same.

The speed contours shown in Figs. 1–3 are a simple measure of the kinetic energy distribution within the pool, which is related to the energy available for weld pool formation and growth (Ref. 32). Changes in the shape of speed contours should, therefore, reflect the factors determining weld pool shape. The depth-to-width ratio is a common way of representing the weld pool shape, so using a similar approach to represent the flow pattern via the depth-to-width ratio of its speed contours seemed appropriate. Accordingly, the depth-to-width ratios of the 0.0625 m/s speed contour were determined for all conditions, and these are presented relative to the standard case in Fig. 4.

For the conditions at a welding current of 100 A, the depth-to-width ratio for the relatively high surface tension drop was 400% greater than the ratio when the surface tension of the pool and drop were the same. For the same surface tension differences, this variation was only 3% at a welding current of 200 A. Similar results also apply in the case of a relatively low surface tension drop, as also shown in Fig. 4.

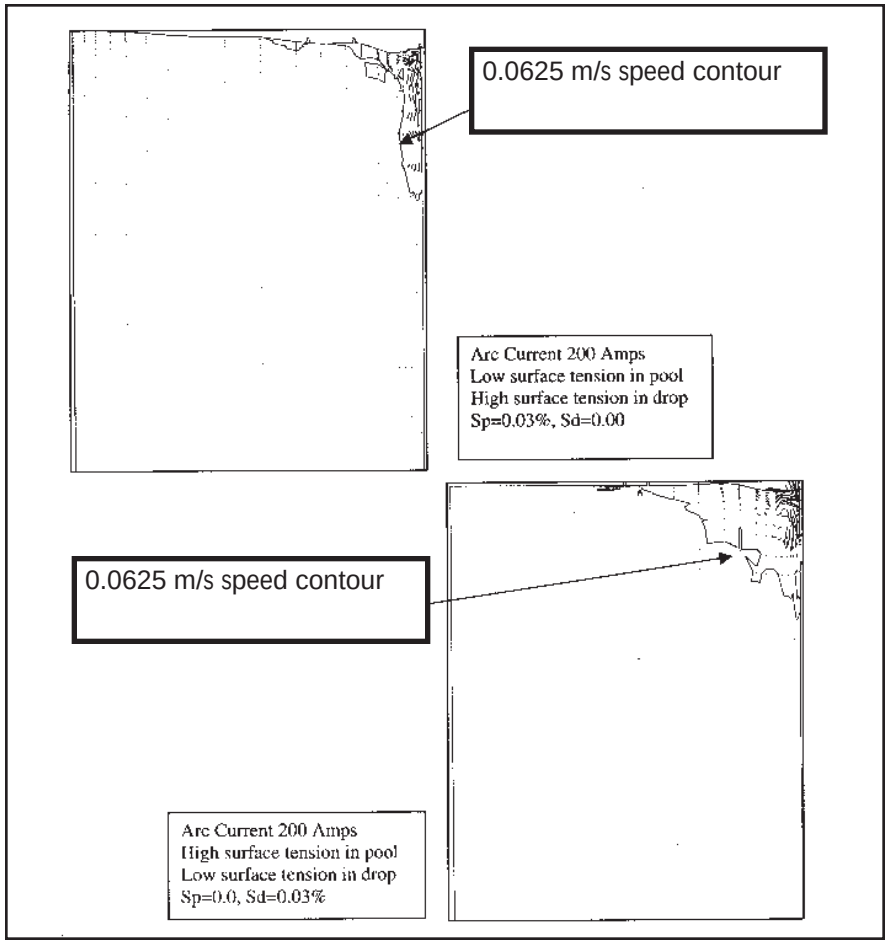

Fig. 3 — Predicted flow patterns showing flow direction and superimposed 0.0625 m/s speed contour for an arc current of 200 A. In the top view, the pool has a lower surface tension than the drop, and in the bottom view, the pool has a higher surface tension than the drop.

While these effects may not be of the same magnitude as changes in weld pool shape, they are indicative of the expected trends, and to test these, an experimental appraisal of the influence of surface tension on weld pool geometry was carried out. The experiment consisted of producing a central bead-on-plate weld on a 10-mm-thick mild steel plate, under the conditions given in Table 3. One section of the plate was coated with FeS and one left in its "natural" state. Instead of the welding wire, the plate surface was doped to avoid possible effects from varied metal transfer behavior. The resulting welds were then cross sectioned and the pool geometry determined for both the doped and natural regions. The weld metal in the doped region showed a 0.02% increase in sulfur compared to the natural region, giving an estimated 10% reduction in surface tension. Figure 4 includes the measured weld bead depth-to-width ratio for the doped surface expressed relative to that for the undoped one at two welding current levels. The influence of sulfur (reduced surface tension) is much greater at the low welding current, hence the experimental values show the same trend as the computed results.

It seems clear the variation in the surface tension effect is due to the relative magnitude of the surface tension and momentum flux. At a welding current of 100 A, the momentum of the droplet stream is significantly lower than at 200 A, and it appears that as the welding current increases, the contribution from higher momentum forces completely swamps the contribution due to the concentration-gradient-driven surface tension flow. There are two main reasons for this. First, the impact velocity at low current is

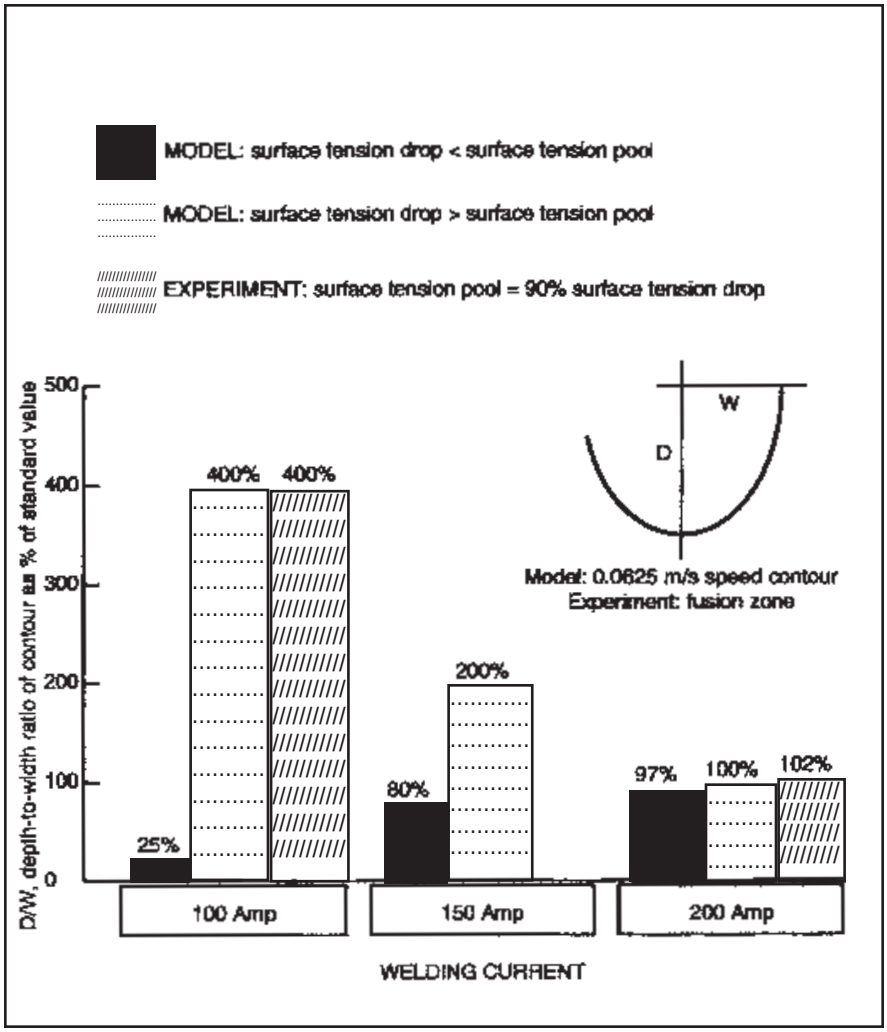

Fig. 4 — Depth-to-width ratios of the characteristic speed contour from computational models of different droplet-pool conditions, together with experimental data from the fusion zone of bead-on-plate welds.

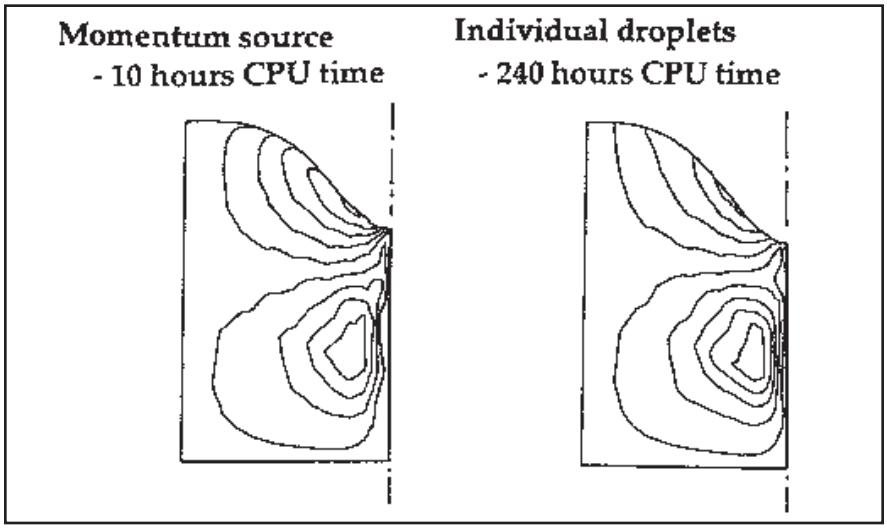

Fig. 5 — A comparison of predicted stream function contours (0.0001 increments) generated from a model simulating individual droplet impact and from one treating droplet impact as a momentum source.

lower than at a high one, and second, the frequency of impact at low current is significantly lower than at high current. These changes indicate an increase in the total momentum transferred as the welding current is increased. A simple calculation shows the momentum transfer in 1 s at 100 A is only 12% of that transferred at 200 A, whereas the surface tension effect would remain approximately the same. This relatively small contribution from surface-tension-driven flow at high welding current is also in agreement with the measured values of impact velocity (1.5 ms^{-1}) (Ref. 28) and surface tension induced flow (0.06–0.20 ms^{-1}) (Ref. 21).

Based on the above results it seems reasonable to ignore the influence of a difference in droplet and pool surface tension when modeling weld pools for welding currents above about 150 A, and this finding has implications on the type of computer model needed. In any practical model of the weld pool, the tracking of temperature is of crucial importance, and the effect of temperature-dependent surface tension can be easily incorporated. However, to track the local concentration of surface-active elements in the pool means solving another set of transport equations, making the computation significantly more expensive and numerically less stable.

It is recognized that surface-active elements have a significant role in GTA weld pool flow, where their presence can reverse the flow direction and radically change the weld profile. However, as there is no metal transfer in most GTA weld pool models, the surface tension is simply determined as a function of the overall pool composition and the local temperature. This situation will also hold in a GMA weld pool if the relative surface tensions between the droplet and the pool do not produce significant effects on the flow. In that case, it would not be necessary to track the local variation of composition within the pool and the task of modeling a GMA weld pool would be simplified.

Another significant simplification would come from avoiding the need to treat metal transfer as individual droplets. Because of the dominance of the droplet momentum at welding currents 150 A, one option is to represent the transferred droplets as a heat and momentum source. Clearly, for this approach to be valid, a model treating them as such should predict the same flow pattern as one treating them as individual droplets. Two such models were developed and used to predict the weld pool flow pattern at a quasi-steady state. A weld at a current of 200 A was modeled, providing conditions under which the relative droplet/pool surface tension effects

should be negligible.

The predicted flow profiles and velocities are similar for both models. Figure 5 compares the predicted streamline contour plots. However, there are significant differences in computational efficiency. The momentum source model does not track local compositional variations and used surface tension values based on average pool composition and local temperature, and since it does not treat individual droplets it can use significantly larger time steps. The momentum source model took approximately 10 h of CPU time on a Sun workstation and the individual droplet model took 240 h. This indicates that by treating transferred droplets as a heat and momentum source, significant savings in computational time and cost can be made, without sacrificing accuracy.

In Fig. 5, the steady-state deformation of the pool surface for a weld current of 200 A is shown to be significantly larger than that shown in Fig. 3, indicating the pool surface continues to deform to a steady-state case. Figure 3 shows conditions after a single droplet impact.

Conclusions

A computational model of the interaction between a droplet and a liquid pool has demonstrated that the flow induced by the relative surface tensions of the droplet and the pool only has an influence on flow patterns for welding currents less than 150 A. For welding currents approaching 200 A, the increased droplet momentum dominates the flow pattern and overrides any surface tension effects. This result has been supported by experimental investigations.

This study demonstrated with direct-current GMA weld pools and welding currents of 150–200 A, it is not necessary to model the local variation in surface-active elements, therefore reducing the number of transport equations that need to be solved and decreasing the complexity and running times.

In addition, it is shown for such cases it is possible to model the droplet transfer as a heat and momentum source, significantly simplifying the task and increasing the efficiency of modeling flow within a GMA weld pool.

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