Modelling of GTAW Weld Pool under Marangoni Convection

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INTRODUCTION

With several different fusion welding processes, the melted weld pool profile which ultimately solidifies to form the fusion zone, diverging greatly by a wide variety of factors, e.g. base material, workpiece size, machine setups and extensive range of other process variables. For each distinctive welding setup, the weld pool geometry could vary considerably, and thought to be largely dependent on the hydrodynamics of the weld pools [1].

The Marangoni Effect or thermo-capillarity is seen to be the a dominant force influencing weld pool flow patterns under Gas Tungsten Arc Welding (GTAW), inducing liquid metal to flow to regions with higher surface tension (γ) caused by surface tension thermal gradients $\partial\gamma/\partial T$, this in turn would greatly alter the weld pool thermal history, hence the fusion zone geometry [2]. As a general trend, for a negative $\partial\gamma/\partial T$, outward flow from the pool centre to the edge tends to produce wide and shallow pools; whereas for a positive $\partial\gamma/\partial T$, the liquid metal would flow inward to the pool centre, thus creating deep and narrow pool shapes [3].

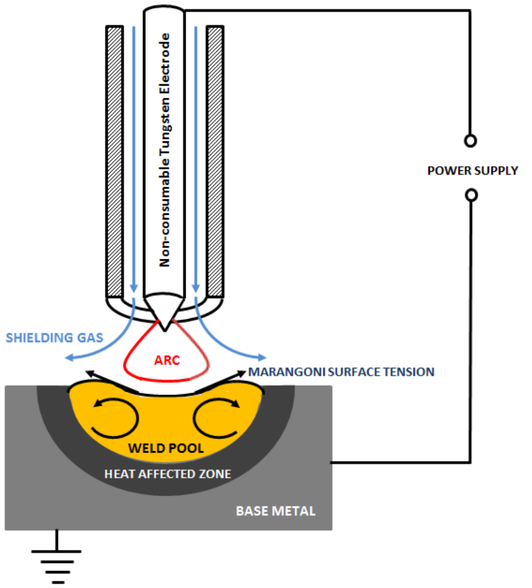

Fig. 1 Schematic illustration of GTAW process with negative surface tension temperature gradient.

This research group believes that the Marangoni Effect is the dominant force in weld pool shaping. To better understand the weld pool behaviours, a two-dimensional simulation model was constructed in CFD package Fluent®, based on stationary arc GTAW welding conditions. In addition, GTAW welding experiments were also performed on titanium alloy Ti-5Al-5Mo-5V-3Cr as reference data for the numerical results to evaluate against.

NUMERICAL MODELLING

The axisymmetric weld pool model is shown below in Fig. 2, some major assumptions were made: (1) flat surface with no surface deformations; (2) standard k-ε turbulent model; (3) fluid as incompressible Newtonian; (4) gas phase is ignored; (5) Gaussian distribution of the heat flux; (6) arc plasma force small enough to be ignored; (7) ambient conditions as $T_a = 300\ K$ & $P_a = 101.325\ kPa$.

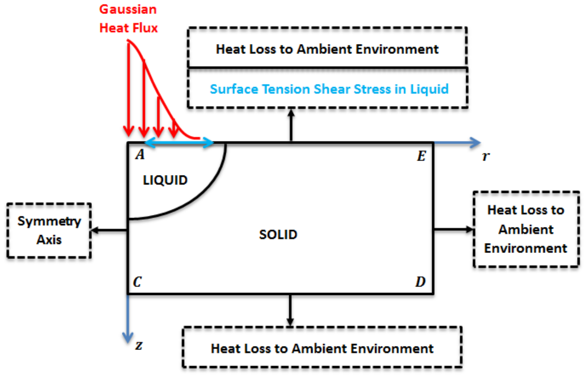

Fig. 2 Schematic illustration of the simulation setup and temperature and velocity (surface tension force) boundary conditions.

Four evident forces are present during the GTAW process: surface tension forces, electromagnetic forces, buoyancy forces and arc plasma forces [4]. The governing laws of the model are conservation of mass, momentum and energy equations. Problem specific source terms were written in high level programming language. The momentum source and sink terms, to account for electromagnetic force and buoyancy force as well as identifying and forcing zero velocity in the solid phase; the energy source term, which represents the energy absorption for latent heat of fusion.

GTAW EXPERIMENTS

Titanium alloy Ti-5Al-5Mo-5V-3Cr were spot welded in an incrementing time step of 1s for 5 steps, for two welding currents of 40A and 60A. Samples of metallography indicating the fusion zones are illustrated in Fig. 3.

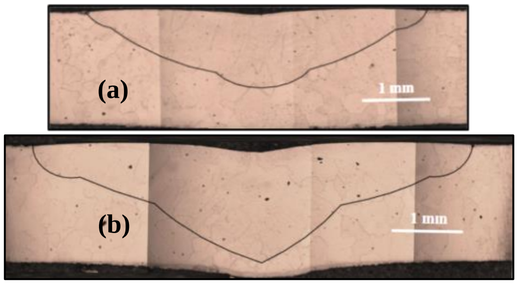

Fig. 3 Examples of Ti-5Al-5Mo-5V-3Cr fusion zone metallography; (a) 10V & 40A for 5 seconds; (b) 10V & 60A for 3 seconds.

SIMULATION RESULTS

Sensitivity analysis on the model was performed with varying degree of surface tension temperature gradients from -0.0005 to 0.0005 $\mathrm{N/m \cdot K}$ in steps of 0.0001 $\mathrm{N/m \cdot K}$; its influence on the maximum weld pool temp-erature, maximum fluid velocity (negative being outward flow) and the weld pool aspect ratio were investigated as demonstrated in Fig. 4 & Fig. 5.

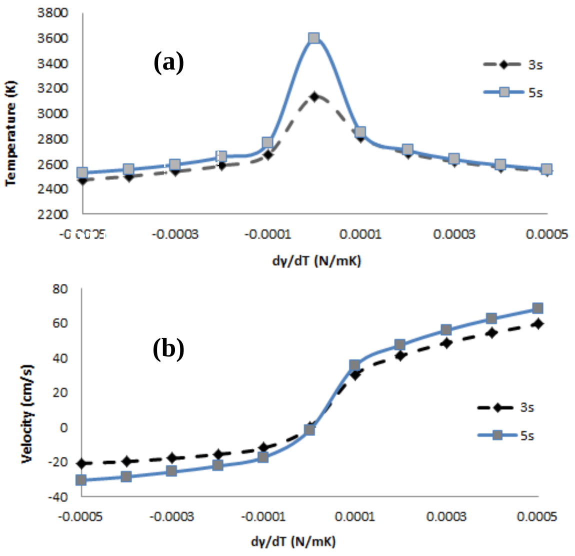

Fig. 4 Variations of $\partial\gamma/\partial T$ under 40A with respect to: (a) maximum weld pool temperature; (b) maximum fluid velocity.

The weld pool temperature gradually increased as the surface tension thermal gradient moved towards zero, where the maximum temperature peaked usually high as seen in Fig. 4 (a). With absence of surface tension force, thermal mixing stimulating conductivity could not be fully utilised, instead localising the heat transfer inducing higher weld pool temperature and buoyancy force.

Furthermore, by examining the effect of surface tension temperature gradient on the flow velocities, interesting observations on the magnitude of the forces associated with the weld pool could be revealed. At $\partial\gamma/\partial T = 0$, a very small negative (outward flow) velocity was usually induced, less than 2 cm/s in magnitude, reinforcing the theory that for GTAW process, surface tension forces would have the most profound impact; the outward flow direction suggests that buoyancy forces (outward flow) would outweigh electromagnetic force (inward flow), since these are the only two forces existing in this model. Moreover, the velocity magnitudes for positive gradients are much larger than when negative, this may be due to the fact that gravitational force would stimulate the inward flow, further speeding up the circulating flow initiated from the top surface.

As one would expect, by varying the surface tension thermal gradient from negative to positive, the weld pool geometry went from wide and shallow to deep and narrow; also the width, depth and aspect ratio tends to increase/decrease in a linear pattern, without any critical points as seen in Fig. 5.

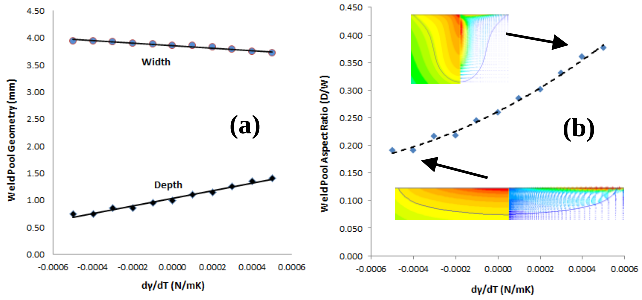

Fig. 5 Influence of $\partial\gamma/\partial T$ on the weld pool geometry: (a) size of width and depth; (b) pool aspect ratio (D/W).

COMPARISON OF RESULTS

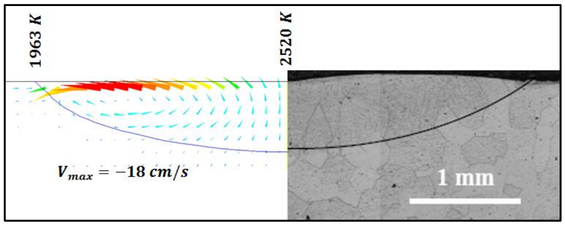

Fig. 6 Simulation result compared with experimental result under 40A for 3 seconds and $\partial\gamma/\partial T \approx -0.00035\ N/m \cdot K$

Almost all welding simulations up to today incorporated a simple yet crude way to make up for momentum and energy under calculations, known as enhancement factor, in which it is applied to liquid thermal conductivity and viscosity [5]; this deficiency is largely due to difficulties in measuring viscosity temperature dependent data, thus a nominal/average value of viscosity is often used.

As for the current study, the weld pool shape had a good agreement with an enhancement factor of 2, negative surface tension temperature gradients was also discovered with slight variations for the two power settings, $-0.00035\ N/m \cdot K$ for the 40A case and $-0.0004\ N/m \cdot K$ under the 60A scenario.

CONCLUSIONS

Marangoni convection is the principal force in influencing weld pool heat transfer and fusion zone shape, followed by buoyancy force and electromagnetic force; however the latter two are minimal when compared to surface tension. Ti-5Al-5Mo-5V-3Cr under investigation was found to constitute high negative $\partial\gamma/\partial T$ values during GTAW process, overall good agreement of simulation results to experimental data was obtained by a relatively low enhancement factor of 2.

ACKNOWLEDGEMNTS

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