FLUID FLOW AND ITS DRIVING FORCES IN LASER DISSIMILAR WELDING OF STAINLESS STEEL AND NICKEL

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Summary A 3D heat and mass transfer model is used to simulate the welding process, based on the solution of the equations of mass, momentum, energy conservation and solute transport in weld pool. Dimensional analysis reveals that the fluid flow is mainly driven by Marangoni convection and to a much less extent by the buoyancy force. Marangoni stresses due to temperature gradients and concentration gradients are analyzed and compared. Calculated weld pool dimensions are compared with the corresponding experimental results.

INTRODUCTION

Use of different metals and alloys in a product provides the designers and engineers with great flexibility, which often results in both technical and economic advantages over conventional manufacturing methods by using a single material. However, because of the difference in physical and chemical properties of two metals, many problems, such as partial penetration due to insufficient heat dissipation, brittle intermetallic compound or low melting point eutectics formation due to inappropriate solute dilution or heat treatment in joining dissimilar metals, may make the joint susceptible to cracks and failures[1].

Numerical simulation on heat and mass transfer is helpful in prediction of temperature and composition for different processing parameters. In recent decades, computational models of heat transfer and fluid flow have been utilized to understand the evolution of temperature and velocity fields for similar metal welding applications[2-3]. However, only few studies[4] addressed the modelling of dissimilar metal welding. In this work, a 3D heat and mass transfer model is developed to study laser spot welding of stainless steel and nickel. Marangoni stresses due to both temperature and concentration gradients and buoyancy force are considered and analyzed. The calculated weld pool dimensions are compared with the corresponding experimental results to validate the model.

MATHEMATICAL MODELING

In this work, the following assumptions are made to simplify the calculations:

1. The molten metal is supposed to be Newtonian and incompressible, and the Boussinesq's approximation is used to account for the density change due to the temperature and concentration variations. The fluid flow is laminar.
2. The welding takes place in conduction mode, and the free surface of the pool is flat.
3. The incident flux of the laser beam at the top surface of the workspace is Gaussian.
4. Relevant physical and thermal properties of the weld pool metal, such as thermal conductivity, specific heat, surface tension and viscosity, vary linearly with composition.

The frictional dissipation of momentum in the mushy zone is modelled according to Carman-Kozeny equation for flow through porous media. Buoyancy effects caused by temperature and concentration variations are incorporated in the source terms of momentum equations. The latent heat during phase change is considered by introducing liquid mass fraction. Vaporization of alloying elements is ignored, since the temperature of weld pool is below the boiling point of materials. At the top surface, the boundary condition for energy equation is given by,

$$K\frac{dT}{dz}=\frac{aQ\eta}{\pi r_b^2}\exp\left(-\frac{a(x^2+y^2)}{r_b^2}\right)-h_c(T-T_a)-\sigma_b\varepsilon(T^4-T_a^4)$$

The Marangoni-driven flow at the free surface is described by,

$$\mu\frac{du}{dz}=f_l\frac{\partial\sigma_{sur}}{\partial T}\frac{\partial T}{\partial x}+f_l\frac{\partial\sigma_{sur}}{\partial C}\frac{\partial C}{\partial x},\quad \mu\frac{dv}{dz}=f_l\frac{\partial\sigma_{sur}}{\partial T}\frac{\partial T}{\partial y}+f_l\frac{\partial\sigma_{sur}}{\partial C}\frac{\partial C}{\partial y}$$

RESULTS AND DISCUSSION

The concentration profile of Fe at the top surface for different times is shown in Figure 1. The weld pool dimension at the stainless steel side is always larger than that at the Nickel side, due to relatively less conductivity. There are mainly two kinds of driving forces for fluid flow in the weld pool, namely buoyancy and Marangoni force which result from temperature or concentration gradient. Dimensional analysis reveals that Grashof number is on the order of 10^2, while Marangoni numbers due to temperature gradient and concentration gradient are on the order of 10^5 and 10^3, respectively. Thus it can be expected that the liquid flow is mainly driven by Marangoni convection and to a much less extent by the buoyancy force. Furthermore, the relative value of the dimensionless numbers (Ma_T and Ma_C) indicates that temperature gradient effect is more important than concentration gradient effect in driving the fluid flow.

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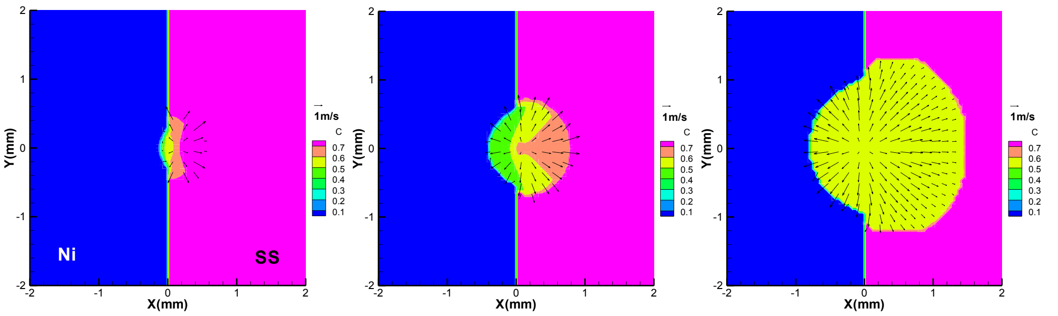
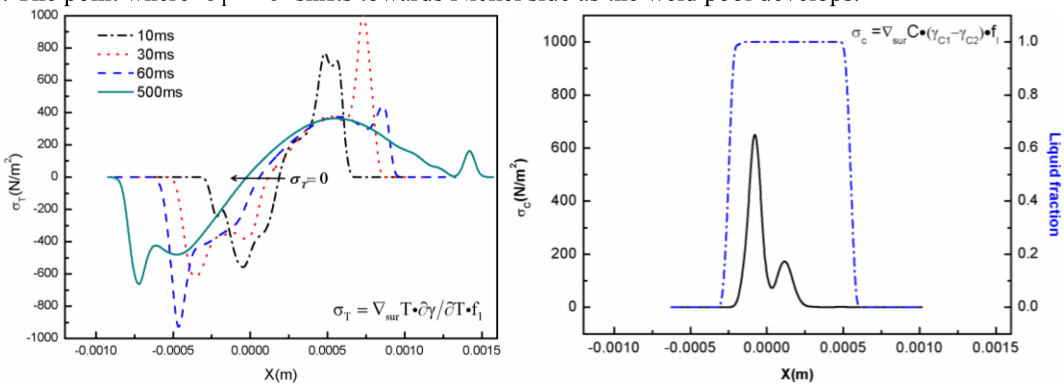


(a) (b) (c)

Figure 1. Weld pool dimension and element Fe distribution at (a)10ms, (b)40ms, (c)500ms

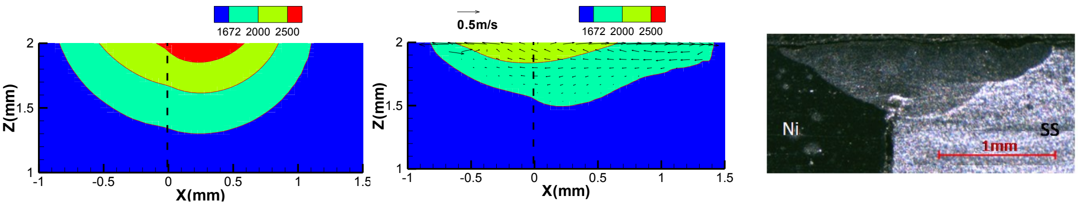
The evolution of Marangoni stresses due to temperature gradient σ_T and concentration gradient σ_c at the initial stage of weld pool are given in Figure 2. The magnitudes of both stresses are comparable(about $10^2 N/m^2$) during the initial stage of melting. However, while σ_c is always positive inside the weld pool(dragging the fluid flow towards stainless steel), σ_T has different signs at stainless steel and Nickel(dragging the fluid flow from the centre towards periphery). Furthermore, while σ_T always exerts on the melt metal, σ_c diminishes quickly as elements become uniformly distributed. The point where $\sigma_T = 0$ shifts towards Nickel side as the weld pool develops.



(a) (b)

Figure 2. Calculated Marangoni stresses along the symmetrical line of the weld pool (a) σ_T, (b) σ_c

The experimentally determined weld pool cross section is compared with the corresponding computed results in Figure 3. It is observed that the calculated weld pool geometry and dimensions, when fluid flow is considered, agree better with the experimental results, while the fusion zone without considering fluid flow is much deeper and narrower. The dimension of the fusion zone at the nickel side is smaller than the radius of laser beam (1.0mm), because of the high conductivity of solid nickel. On the contrary, the fusion zone (1.4mm) at the stainless steel side is much larger, and its dimension exceeds the radius of laser beam.



(a) (b) (c)

Figure 3. Weld pool cross sections: (a) Without considering fluid flow (b) considering fluid flow (c) from experiment

CONCLUSIONS

The weld pool dimension at the stainless steel side is larger than that at the Nickel side. The liquid flow is mainly driven by Marangoni convection. Marangoni stresses due to temperature gradient and concentration gradient have comparable magnitudes at the initial stage of melting but have different trends as weld pool develops. Calculated weld pool dimensions when fluid flow is considered agree better with the experimental results.

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