International Journal of Heat and Mass Transfer 55 (2012) 2328–2337

Contents lists available at SciVerse ScienceDirect

International Journal of Heat and Mass Transfer

journal homepage: www.elsevier.com/locate/ijhmt

Scaling weld or melt pool shape induced by thermocapillary convection

P.S. Wei *, H.J. Liu, C.L. Lin

Department of Mechanical and Electro-Mechanical Engineering, National Sun Yat-Sen University, Kaohsiung, Taiwan, ROC

ARTICLE INFO

Article history:
Received 7 October 2011
Received in revised form 12 January 2012
Accepted 18 January 2012
Available online 20 February 2012

Keywords:
Laser welding
Electron beam welding
Thermocapillary convection
Moving boundary
Scale analysis

ABSTRACT

The molten pool shape and transport variables induced by thermocapillary force during welding (or melting) of workpieces, such as pure iron, titanium, high speed steel and stainless steel alloys, can be self-consistently predicted from scale analysis. Determination of the molten pool shape and transport variables is crucial due to their close relationship with the microstructures, strength and properties of the fusion zone. In this study, the pool excludes a strongly wavy bottom and the surface velocity profile has two peaks valid for Prandtl numbers lying between 0.3 and unity. The surface tension coefficient is negative and suitable for all pure liquid metals and alloys containing minor surface active solutes, giving rise to an outward surface flow. In view of high Marangoni number, the domain of scaling is divided into the hot and cold corner regions, boundary layers on the solid–liquid interface and ahead of the melting front. The results find that the width and depth of the pool, peak and secondary peak surface velocities, and maximum temperatures in the hot and cold corner regions can be explicitly and separately determined as functions of working variables, or Marangoni, Prandtl, Peclet, Stefan, and beam power numbers and solid-to-liquid thermal conductivity ratio. The scaled results agree with numerical data and available experimental data. This work has academic and practical importance. Successful scaling not only reveals physical mechanisms, but also provides quantitative predictions of the fusion zone shapes and transport variables prior to melting or welding.

1. Introduction

Microstructure and properties of workpieces after welding, melting, crystal growth, etc. are strongly determined by convection induced by thermocapillary force [1–6]. Thermocapillary flow is the flow driven by a temperature-dependent surface tension gradient along the free surface. Provided that surface temperature decreases in outward directions, energy transport induced by thermocapillary surface flow with a negative surface tension coefficient ($d\gamma/dT < 0$) directs flow from the center to the edge of the pool, leading to a shallow and wide molten pool. On the other hand, the pool becomes narrow and deep for a positive surface tension coefficient. Even though the pool shape and transport variables induced by thermocapillary force have been extensively studied in recent decades [7–12], physical mechanisms and formation of the fusion boundary are still not well understood.

Limmaneevichitr and Kou [13] observed the effects of Prandtl and Peclet numbers on the molten pool shape and Marangoni convection in stationary laser welding of gallium and sodium nitrate. The Peclet number, defined by the product of the pool surface width and maximum surface velocity divided by thermal diffusivity, was actually the Marangoni number. During welding of gallium, low Peclet numbers promoted conduction down into the pool, and resulted in a concave bottom. For welding of sodium nitrate, however, high Peclet numbers promoted outward convection, and the pool bottom was shallow and flat. In the case of a small beam radius the fast outward surface flow turned and penetrated downward at the pool edge, resulting in a convex pool bottom. The molten pool shapes with small Prandtl numbers can be roughly identified by several regions [14]: (i) the molten pool has a hemispherical shape for $Ma_f < 100$, (ii) the bottom of the pool is convex near the centerline for $0.1 < Pr < 1$ and $100 < Ma_f < 10^5$, (iii) the bottom is slightly convex near the centerline of the shallow pool for $0.3 < Pr < 1$ and $Ma_f > 10^5$, and (iv) the bottom exhibits a strong concave shape with concavity depth as high as one-half of the pool width for $Pr < 0.1$ and $Ma_f > 100$ and a concave shape for $0.1 < Pr < 0.3$ and $Ma_f > 10^5$.

Except for very small Prandtl numbers (for example, $Pr = 0.06$), leading to high pool depth, Wei et al. [15] showed that as Marangoni number increases in a range less than 10^3 the decrease in the pool depth is insensitive to the variation of Prandtl number. A further increase in Marangoni number results in the pool depth to continuously decrease and then increase. The minimum pool depth occurs at $Pr = 1$. The corresponding pool width, however, increases and then decreases as Marangoni number increases. Therefore, the width-to-depth ratio of the pool exhibits a rapid increase and then decrease by increasing Marangoni number. The width-to-depth ratio also decreases as Prandtl number decreases. The surface

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* Corresponding author. Tel.: +886 7 5254050; fax: +886 7 5254214.
E-mail addresses: pswei@mail.nsysu.edu.tw (P.S. Wei), ifsfoof@gmail.com (H.J. Liu), sppchaulongspp@yahoo.com.tw (C.L. Lin).

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doi:10.1016/j.ijheatmasstransfer.2012.01.034

Nomenclature

b_1, b_2	empirical constants in Eq. (5)
h	molten pool depth
k	thermal conductivity
L	latent heat for melting
Ma, Ma_f	Marangoni numbers, defined in Eqs. (32) and (13)
Pe_w, Pe_σ	Peclet numbers, defined in Eqs. (6) and (32)
q	incident flux
Q, Q^*	dimensional and dimensionless beam power, defined in Eq. (8)
Ste	Stefan number, defined in Eq. (6)
U	scanning speed
u, v	horizontal and vertical velocity component
w	molten pool width
x, y, z	coordinate, as illustrated in Fig. 1

Greek letters

γ, $d\gamma/dT$	surface tension and surface tension coefficient
δ, Δ	thicknesses of free surface layer, momentum and thermal boundary layers, as illustrated in Fig. 2
σ	energy distribution parameter
η	melting efficiency

Superscript

$*$	dimensionless quantity
$'$	secondary
$''$	along solid–liquid interface

Subscripts

c, C	cold corner
f	free surface
ℓ	liquid
m	melting
s	solid
T	thermal
v	viscous
∞	surroundings
σ	energy distribution parameter

temperature reveals the hot, intermediate and cold corner regions due to irradiation in the hot region and cooling near the edge of the pool. Surface temperature thus exhibits significant drops, leading to peak surface velocities near the edge of the hot region and in the cold corner region, respectively. However, only one peak surface velocity occurs in the cold corner region for Prandtl number less than 0.3 [14]. Surface temperature in the hot region decreases with increasing Prandtl and Marangoni numbers. Irrespective of Prandtl number, the peak surface temperature increases with decreasing Peclet number or welding speed, and increasing beam power.

Physical mechanisms of the pool shape and transport variables induced by thermocapillary force can be quantitatively and systematically revealed from scale analysis often used in heat transfer and fluid mechanics fields [16]. Ostrach [17] was one of the earliest researchers to study thermocapillary flow from scale analysis. By considering tangential shear stress to be the same order of magnitude as thermocapillary and inertial forces in the shear layer beneath the free surface, the maximum surface speed was found to be proportional to the surface tension coefficient to the 2/3 power or $Ma^{2/3}$. Chen [18] reviewed the scaling of thermocapillary convection in material processing for different Prandtl numbers. Scale analysis of thermocapillary convection was conducted in distinct regions in rectangular cavities subject to a centrally applied distributed heat flux and differential wall temperatures, respectively. In order to satisfy momentum, energy and mass balances, the former included a hot corner, a free surface layer, a cold corner, a side wall boundary layer and core regions. It was proposed that scaling of the hot corner and free surface layer can be from Ostrach [17], the cold corner region from Zebib et al. [19], the core region from Cowley and Davis [20], and the boundary layer on the wall from conventional boundary layer theory, respectively. Comparisons of the scaled variables with numerical predictions and experimental data, however, were not presented. Kamotani et al. [21] also scaled the effects of constant flux heating modes near the axisymmetric axis on thermocapillary flows in a cylindrical container. For small Prandtl number and high Marangoni number the peak surface velocity and the beam power divided by temperature difference are proportional to the surface tension coefficient to the 2/3 power and the 1/3 power, respectively. Kamotani and Ostrach [22] reconsidered the model from Cowley and Davis [20] by further accounting for a cold wall and thermocapillary flow driven by temperature drop near the hot corner region for high Prandtl numbers. The thermocapillary pool shape induced by incident flux, however, has not been presented in the literature.

In this study, unknown fusion zone shapes coupled with thermocapillary convection for low Prandtl numbers during low-power-density-beam welding or melting are self-consistently scaled. Different from previous studies, this work deals with a free boundary problem coupling with distinct boundary layers in different regions. This work has academic and practical importance. Successful scaling not only reveals physical mechanisms, but also provides quantitative predictions of the fusion zone shapes and transport variables prior to melting or welding.

2. System model

Welding is conducted with a distributed low power-density laser or electron beam moving at a constant speed U along the joint line, as illustrated in Fig. 1(a) [23]. A typical flow field and fusion zone shape on a transverse x–y cross-section is sketched in Fig. 1(b). For a negative surface tension coefficient thermocapillary surface flow accompanying energy transfer is from the center to the edge of the pool, as shown in Fig. 1(c). High temperature gradient thus occurs near the pool edge. The major assumptions are described in a previous work [23]. That is,

(1) The use of low power-density beam implies the absence of the keyhole in the molten pool. In the case of high-power-density beam welding, a keyhole is produced due to strong surface flow induced by thermocapillary force and recoil pressure directs in outward and upward directions [24–26].

(2) The surface of the pool is flat. This can be confirmed by a small capillary number $(Ca \equiv (d\gamma/dT)\Delta T/\gamma_m)$ [27]. Typical metals surface tension coefficient $d\gamma/dT \approx -10^{-4}$ N/m–K, temperature difference across the free surface $\Delta T \approx 1000$ K, and surface tension at the melting point $\gamma_m \approx 1$ N/m. The capillary number is 0.1. More relevant estimation for deformation of the free surface can refer to the scale law provided by Wei [6]. It indicated that surface deformation can be neglected if surface velocity, density and molten pool width reduced and surface tension increased.