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Prediction of pore size in high power density beam welding

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This study is to investigate parameters responsible for the final pore size during high power density laser and electron beam welding processes. Dimensionless parameters include the surface tension parameter, Mach number and liquid pressure at the keyhole base, friction factor, melting temperature, ratio of specific heats at constant pressure and volume, and loss coefficient. The friction factor can also be treated as a combination of viscous shear stress and thermocapillary force. Although the formation of macroporosity is recognized as an important problem that limits the widespread industrial application of laser and electron beam welding, the physics of the macroporosity formation is not well understood. In order to solve this problem, both the states at the times when the keyhole is about to be enclosed and the pore is completely formed are considered to be governed by the equation of state. The pore shape thus can be determined by the Young–Laplace equation. The gas pressure is determined by calculating a compressible flow of the two-phase, vapor–liquid dispersion in a vertical keyhole of varying cross-section, paying particular attention to transition between the annular and slug flows. It shows that regardless of a supersonic or subsonic flow at the base, the final pore size decreases as the dimensionless surface tension parameter, liquid pressure at the keyhole base, and melting temperature decrease. The pore size also decreases with increasing friction factor subject to a supersonic flow at the base. The effects of the ratio of specific heats at constant pressure and volume, friction factor and loss coefficient on the final pore size are insignificant for a subsonic mixture. This work provides a systematical understanding of the factors affecting the final pore size during keyhole mode welding.

1. Introduction

High power density laser and electron beam welds often contain porosities [1–5]. The resulting degradation of mechanical properties depends on the size distribution and volume fractions of pores. Mechanism of porosity can be simply and interestingly revealed by using the Q-mass spectrograph to analyze gas content in pores via drilling the portion of pores in high vacuum. Pores are found to be mainly composed of metal vapor and some entrained shielding gas and air in the keyhole. Pastor et al. [6] thus explained the mechanism for the formation of porosity to be caused by the collapse of unstable keyhole. When pressure due to surface tension exceeds vapor pressure, projections occur inside the keyhole. The projections increase in size with surface tension until gravitational force dominates projections. The keyhole collapse and pore thus is formed.

The keyhole oscillates in very complex and unstable manner, as first experimentally observed by Tong and Giedt [7,8] using a high energy pulsed X-ray source. The radiographs not only verified the existence of the keyhole but also showed its oscillations in size and shape. The oscillatory nature of the cavity provided an explanation for welding defects such as spiking, and porosity at the tip of the fusion zone, as shown in Fig. 1 [9]. In this case, serious pores are in lengths of 0.5 to 1 mm in the welding of Al 5083 subject to the focal spot above the surface by 20 mm, and welding speed of 15 mm/s. Al 5083 contains a significant amount of volatile element Mg. Arata [10] and Katayama and Matsunawa [11] also used a microfocused X-ray transmission imaging system to observe pore formation affected by fluid flow, showing that large bubbles were primarily formed at the bottom of the keyhole.

A confirmative study of pore formation in keyhole welding requires a systematical and theoretical understanding of fluid flow and heat transfer through the keyhole experiencing its collapse. Lee et al. [12] numerical studied the formation and stability of a stationary laser weld keyhole. The keyhole is formed by displacement of the melt induced by evaporation recoil pressure based on the local equilibrium temperature, while surface tension and

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Nomenclature

A_c	cross-sectional area of keyhole, $A_c = \pi r_c^2$
f_{im}	friction factor $\equiv 2\tilde{\tau}_{im}/\tilde{\rho}_c\tilde{u}_c^2$
Fr	modified Froude number, $Fr \equiv R_c\tilde{T}_{cB}/g\tilde{h}$
g	gravitational acceleration
h	keyhole depth
H	total energy, $H \equiv \tilde{H}/\tilde{c}_{pc}\tilde{T}_{cB}$
J_e	local entrainment flux across keyhole wall, $J_e \equiv \tilde{J}_e/\tilde{\rho}_{cB}\sqrt{R_c\tilde{T}_{cB}}$
K	loss coefficient
M_c	Mach number, $M_c \equiv \tilde{u}_c/\sqrt{\kappa R_c\tilde{T}_c}$
p	pressure $p \equiv \tilde{p}/\tilde{p}_{cB}$
$\tilde{p}_{c,a}$	average pressure $\equiv (\tilde{p}_{c,max} + \tilde{p}_{cB})/2$.
Q	absorbed energy = $\tilde{q}/\tilde{c}_{pc}\tilde{T}_{cB}$
r	radial coordinate, $r \equiv \tilde{r}/\tilde{h}$
R_c	specific gas constant
s	arc length along keyhole wall from keyhole tip
T_c	mixture gas temperature, $T_c \equiv \tilde{T}_c/\tilde{T}_{cB}$
$\tilde{T}_{c,a}$	average temperature $\equiv (\tilde{T}_{c,max} + \tilde{T}_{cB})/2$
T_m	melting temperature, $T_m \equiv \tilde{T}_m/\tilde{T}_{cB}$
U	drilling speed, $U^* \equiv U/\sqrt{R_c\tilde{T}_{cB}}$
$\tilde{u}_c$	mixture velocity in keyhole, $\tilde{u}_c = M_c\sqrt{\kappa R_c\tilde{T}_c}$
u_ℓ	liquid layer velocity, $u_\ell \equiv \tilde{u}_\ell/U$
V	welding speed or volume
W_c	axial mass flow rate through core region, $W_c \equiv \tilde{W}_c/\tilde{\rho}_{cB}\tilde{u}_{cB}\tilde{h}^2$
z	axial coordinate, $z \equiv \tilde{z}/\tilde{h}$

Greek letters

Γ	surface tension parameter, $\Gamma \equiv \gamma/\tilde{h}\tilde{\rho}_{cB}R_c\tilde{T}_{cB}$
ρ	density, $\rho \equiv \tilde{\rho}/\tilde{\rho}_{cB}$
κ	specific heat ratio
γ	surface tension
ϕ	axial velocity component ratio between entrained mixture and keyhole mixture

Superscripts

$\sim$	dimensional quantity

Subscripts

a	average
B	keyhole base
c	core region or keyhole
e	entrainment
ℓ	liquid
max	maximum
p	pore
1,2	locations at edge of keyhole base and opening of keyhole

hydrostatic pressure oppose cavity formation. At laser powers of 500 W and greater, the protrusion occurs on the keyhole wall, which results in keyhole collapse and void formation at the bottom. Initiation of the protrusion is caused mainly by collision of upward and downward flows due to the pressure components in the liquid. Zhou et al. [13] numerically showed that pore formation in pulsed laser welding is caused by two competing factors: one is the solidification rate of the molten metal and the other is the backfilling speed of the molten metal during the keyhole collapse process. Porosity formation was found to be strongly related with the depth-to-width aspect ratio of the keyhole. The larger the ratio, the easier porosity will be formed, and the larger the size of the voids. Controlling the laser pulse profile is proposed to prevent/eliminate porosity formation in laser welding. Zhao et al. [14] numerically showed that in continuous laser welding the competition of the dynamic forces and the melt flow results in an unsteady keyhole. Sometimes the keyhole shrinks and collapses suddenly, forms a bubble at the bottom of the molten pool. Porosity will occur if the bubble fails to escape from the molten pool. Pang et al. [15] simulated the self-consistent keyhole shape and weld pool dynamics in deep penetration laser welding. Under certain low heat input welding conditions deep penetration laser welding with a collapsing free keyhole could be obtained and the flow directions near the keyhole wall are upwards and approximately parallel to the keyhole wall. Courtois et al. [16] showed that under high laser power, the keyhole surface undergoes strong instabilities and bubble can appear during the collapse of the keyhole. Depending on the moment of the laser stop, residual porosity may occur. In fact, the initial position of the bubble will determine if the solidification front will have time to capture the bubble.

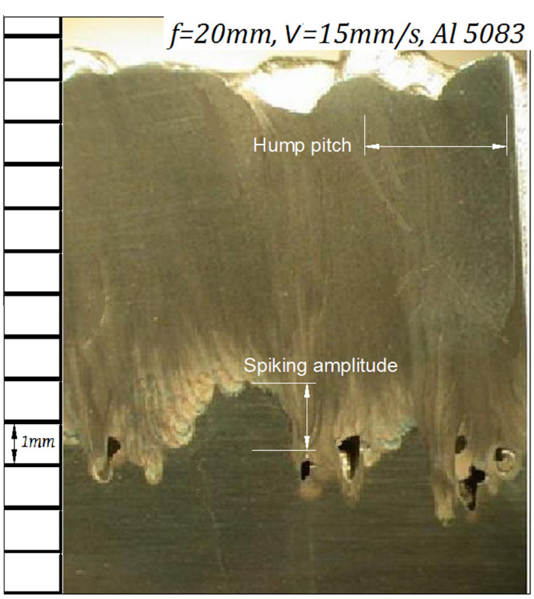

Fig. 1. Porosity occurs in the welding of Al 5083 [9].

The present work proposes a quasi-steady, axisymmetric, and averaged one-dimensional model, which are identical to the annular two-phase vertical flow [17–19], to simulate the pore formation during keyhole mode welding. This simple, general and flexible method has been extensively and efficiently used to investigate the complicated annular two-phase flows and their transitions from annular to slug flows. Slug flow is a liquid–gas two-phase flow in which the gas phase exists as large bubbles separated by liquid slugs. This work provides a systematical and fundamental step to understand the effects of the compressible mixture gas in the keyhole on the formation and final size of a pore taking place at the base.

2. System model and analysis

In this study, the co-ordinate system and geometry of the keyhole are illustrated in Fig. 2(a). For convenience, the solid can be