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Keyhole collapse during high intensity beam drilling

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ABSTRACT

In this study, we identify the conditions for the keyhole collapse during high power density laser and electron beam drilling processes from fundamental principles of thermal physics. Drilling with a high intensity energy beam becomes incapable and inefficient if the keyhole induced is collapsed. Drilling encounters in many diverse industrial application areas including biomedical devices, printers, flat-panel displays, semiconductors devices and telecommunications systems, and keyhole welding. The approach adapted is to probe the quasi-steady, one-dimensional compressible flow behavior of the two-phase vapor–liquid dispersion in a vertical keyhole of varying cross-section, paying particular attention to the transition between the annular and slug flows. Keyhole collapse is interpreted from balance of normal pressures between mixture gas, recoil, liquid and capillary pressures governed by the Young–Laplace equation. It shows that drilling is susceptible to collapse for higher Mach number and radius at the base, friction factor, and ratio of specific heats at constant pressure-to-constant volume, and lower the surface tension parameter, and liquid pressure at the base for a supersonic flow in the keyhole. A subsonic flow usually gives rise to collapse. Controlling the factors to enhance efficiency and quality of drilling therefore becomes achievable.

1. Introduction

Laser or electron beam drilling is applied world-wide in many diverse industrial application areas including biomedical devices, printers, flat-panel displays, semiconductors devices and telecommunications systems, and keyhole mode welding [1–5]. In the production of electrode structures for display panels or the manufacture of channels for micro-fluidic devices, for example, laser drilling can compete with existing conventional processing methods such as photolithography. Photolithography routes involve multiple steps where exposure, wet development and chemical or plasma etching are required. Attractiveness of a laser-based method often lies primarily in it being a single-stage, “dry” process. In other areas such as the production of ink-jet printer nozzles, for example, like nozzle geometry, reproducibility and centricity are not available with competing techniques like electro-discharge machining. Recently, the fabrication of multi-layer electronic packages is developed toward smaller sizes. Small distances between chips together with the short interconnection routes are required to achieve faster operation. via hole formation in insulators have been used to provide vertical interconnections for densely packed three dimensional wiring networks. Drilling with laser or electron beam differs from mechanical drilling in that the focused beam used to create the holes can produce smaller holes than those produced by conventional drilling. Laser drilling capabilities, drilling mechanisms, and hole qualities have been known to depend on laser beam characteristics such as wavelength and beam energy distribution. However, one major which has not been discussed is the collapse of the keyhole induced by thermal and fluid flows. This becomes the aim of this study.

The efficiency of drilling depends on collapse of the keyhole, which is a consequence of balance between gas, liquid and capillary pressures on the wall. Collapse of the keyhole took place if gas pressure was greater than hydrostatic pressure and capillary pressure of the liquid layer [3,6–10]. Understanding of fluid flow and heat transfer in both the keyhole and liquid layer around the keyhole is therefore needed. There have elaborate and rather realistic three-dimensional or axisymmetric models to predict fluid flow and heat transfer during drilling or spot welding [9,11–15], and keyhole welding [16–23]. In the absence of dealing with the gas phase in the keyhole, the gas pressure can be considered as equilibrium pressure at local surface temperature, boiling temperature or the state satisfied by the jump condition of Knudsen layer [9,13,16,19,22]. In the cases of small speeds, the gas phase in the keyhole can be incompressible [11,12,14,17,23]. In reality, gas

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Nomenclature

A_c	cross-sectional area of keyhole, $A_c = \pi r_c^2$
f_{im}	friction factor or friction coefficient $\equiv 2\tilde{\tau}_{im}/\tilde{\rho}_c\tilde{u}_c^2$
Fr	modified Froude number, $Fr \equiv R_c\tilde{T}_{cB}/g\tilde{h}$
g	gravitational acceleration
h	keyhole depth or enthalpy
H	total energy, $H \equiv \tilde{H}/\tilde{c}_{pc}\tilde{T}_{cB}$
h_c	mixture enthalpy, $h_c \equiv \tilde{h}_c/\tilde{c}_{pc}\tilde{T}_{cB}$
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 $p \equiv \tilde{p}/\tilde{p}_{cB}$
q	absorbed energy
Q	absorbed energy parameter = $(d\tilde{q}/d\tilde{z})\tilde{h}/\tilde{c}_{pc}\tilde{T}_{cB}$
r	radial coordinate, $r \equiv \tilde{r}/\tilde{h}$
R_c	specific gas constant
s	arc length along keyhole wall from tip
T_c	mixture gas temperature, $T_c \equiv \tilde{T}_c/\tilde{T}_{cB}$
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, $u_\ell \equiv \tilde{u}_\ell/U$
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

Superscript

$\sim$	dimensional quantity

Subscripts

B	keyhole base
c	core region or keyhole
e	entrainment
ℓ	liquid
1, 2	locations at edge of keyhole base and opening of keyhole

pressure should be determined by considering compressible flow in the keyhole [15,18,20,21]. It should be noted that physical phenomena between drilling and keyhole welding with a high scanning speed can be quite different. For a rapid scanning speed the incident flux cannot reach the keyhole base due to the blockage of the rear wall. The maximum temperature thus cannot occur at the keyhole base, leading to complicated speed, pressure and temperature in the keyhole [18].

Keyhole collapse or pore formation has been numerically revealed and studied by Lee et al. [9], Zhou et al. [11], Amara and Fabbro [20], Zhao et al. [21], Pang et al. [22], and Courtois et al. [14,23]. Lee et al. [9] numerical studied the formation and stability of stationary laser weld keyhole. The keyhole is formed by the displacement of the melt induced by evaporation recoil pressure, while surface tension and 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 recoil pressure and surface tension, respectively. Zhou et al. [11] numerically concluded that the formation of porosity in pulsed laser stationary 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 therefore proposed to prevent porosity formation in laser welding. Amara and Fabbro [20] numerically found that introducing an inert gas jet, the keyhole oscillations disappear. This technique could thus be a means to avoid porosity formation, related to keyhole instability and some gas trapped in the lower part of the keyhole right after the irradiation termination. Zhao et al. [21] numerically found that the keyhole depth self-fluctuates in continuous laser welding. Keyhole collapse and shrinkage are responsible for keyhole-induced porosity. The competition of the dynamic forces and the melt flow resulted in an unstable keyhole. Sometimes it shrinks and collapses suddenly, forms a bubble at the bottom of the molten pool. Pang et al. [22] numerically investigated and confirmed that under certain low heat input deep penetration laser welding the keyhole was stable and the flow direction near the keyhole wall was upwards and approximately parallel to the keyhole wall. However, significantly different weld pool dynamics occurred as the keyhole was unstable. The mechanisms of keyhole instability are found to be closely associated with the behavior of humps on the keyhole wall, affected by welding speed and surface tension. Courtois et al. [14,23] numerically revealed that, under high laser power, the keyhole surface undergoes strong instabilities and bubble can appear during the collapse of the keyhole. The initial position of the bubble will determine if the solidification front will have time to capture the bubble. The number of pores increases with laser power. Evidently, factors affecting keyhole collapse are diverse and unclear. A systematical and parametrical study of keyhole collapse is still lacking.

The present work proposes a quasi-steady, averaged one-dimensional model to simulate collapse of the keyhole. The fluid flow and heat transfer in the molten pool in thin layer surrounding the core region filled with vapor and droplets in the keyhole [24–33] are actually an annular two-phase flow in a vertical pipe. The collapse of the keyhole is the same phenomenon as the bridging of the gas core by liquid from the liquid film and a consequent transition to slug flow. This simple and general method has been extensively used to investigate the complicated annular two-phase flows and their transitions to the slug, churn or mist flows [34–39]. With this method a systematical investigation of the factors affecting the mixture and liquid flows and keyhole collapse is provided in this study.

2. System model and analysis

The co-ordinate system and the physical model are illustrated in Fig. 1. For convenience, the solid can be considered as moving upward at a constant speed $\tilde{U}$ relative to the liquid. A cylindrical coordinate system is chosen with the origin at the keyhole base on the axisymmetric axis pointed in the upward direction. In view