International Communications in Heat and Mass Transfer 68 (2015) 178–187

Contents lists available at ScienceDirect

International Communications in Heat and Mass Transfer

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

A computational analysis of heat transfer and fluid flow in high-speed scanning of laser micro-welding☆

Asghar Hozoorbakhsh *, Mohd Idris Shah Ismail, Nuraini Binti Abdul Aziz

Department of Mechanical and Manufacturing Engineering, Faculty of Engineering, Universiti Putra Malaysia, 43300 UPM, Serdang, Selangor Darul Ehsan, Malaysia

ARTICLE INFO

Available online 26 September 2015

Keywords:
Laser micro-welding
Computational fluid dynamics (CFD)
Heat transfer and fluid flow analysis

ABSTRACT

A transient three-dimensional model is numerically developed using computational fluid dynamics (CFD) method to understand some critical criteria such as temperature fields and melt pool formation by considering the heat source and the material interaction and the effect of laser welding parameters on laser micro-welding process. To gain more implicit insight of fluid dynamics, the issue of circulation of molten metal assisted by the surface tension, buoyancy and recoil pressure forces in the weld pool has been investigated Assuming that atmospheric and vaporised material pressures are balanced at the front of the laser beam. The governing equations from the Navier–Stokes for Newtonian fluid are prepared to estimate the melt flow that influences the rate of temperature distribution in a 3-D domain. The simulation results have been compared with two sets of experimental research to predict the weld bead geometry and solidification pattern which laser welds are made on thin stainless steel sheet (SUS304). The shape comparison describes those parameters relevant to any changes in the melt dynamics and temperatures are of great importance on the formation of weld pool and heat distribution during laser micro-welding. The fair agreement between simulated and experimental results, demonstrates the reliability of the computed model.

1. Introduction

Light amplification by stimulated emission of radiation or laser with the characteristic of being parallel, coherent, monochromatic and convergent beam of electromagnetic radiation. The wavelength is between the ultraviolet to infrared area. Laser can deliver extremely low (~mW) to very high (1–100 kW) concentrated power with an accurate dimension of spot size and spatial or temporal distribution on a given substrate through any intervening medium [1].

Microfabrication progresses have established opportunities to manufacture of the micro-scale structures. These opportunities are useful to create the optical, electronic, biological and magnetic which are ranging from sensors to computation and control systems. Micro-welding is an effective technique for manufacturing process in cases that the attributes of macro-machining can be reduced in size to the micro-scales. In addition, laser beam joining technique has the high rating in the microsystem technology besides macro-range industrial manufacturing processes [2].

Very sensitive response has been shown to heat input in weld bead by thin metal sheets, and the geometry of weld bead has a significant role in the strength of joining. Conventional techniques face some difficulties in thin metal sheet welding, for example, some blow holes can be created in the weld bead because of extreme heat input. Thus, heat input minimization to thin metal sheet is too important economically and technically. From the economic point of view, less heat input needs lower laser power which results in low running cost and minor equipment investment. Technically, smaller heat input ends up, less heat affected zone (HAZ), and finally little material loss due to evaporation [3].

Brown and Banas earlier [4] outlined the earliest study on deep penetration laser beam welding (LBW). The potential scope of the application of pulsed laser welding was earlier outlined by Ready [5], Duley [6] and Schawartz [7]. Li and Gobbi [8] and Schubert et al. [9], Berretta et al. [10], Majumdar and Manna [1] have given a brief overview of the potential applications of CO_2 and Nd:YAG lasers and AISI 304 stainless steel laser welding.

The ability of physical process simulation on a computer is one of the advances in the last century. Mathematical solution of the governing partial differential equations made possibility to simulate the fluid flow, heat transfer and associated processes. The computational simulation and analytical solution have application in industrial purposes and academic research. Some primarily focus on the numerical calculation application to solve specific problems of fluid flow and heat transfer in laser micro-welding have been investigated by Bag and De [11], Bag et al. [12] and Volpp [13] as numerical modelling based on mathematical calculation. The works that mainly deal with the simulation development of mathematical technique are presented by Kuang et al. [14], Kazemi and Goldak [15], Kim et al. [16], Shanmugam et al. [17], Belhadj et al. [18], Sabbaghzadeh et al. [19], Shanmugam et al. [20]

☆ Communicated by W.J. Minkowycz.

* Corresponding author.
E-mail address: a_hozoorbakhsh@yahoo.com (A. Hozoorbakhsh).

http://dx.doi.org/10.1016/j.icheatmasstransfer.2015.08.013

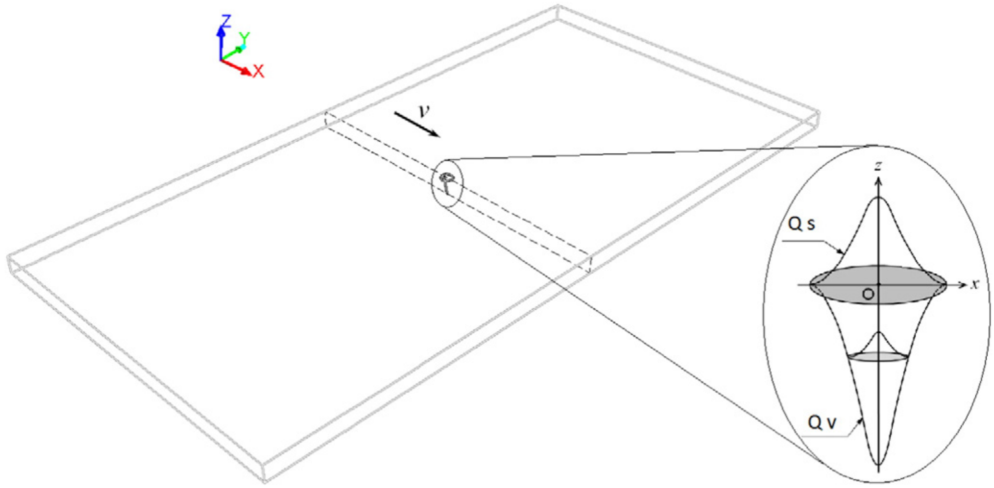

Fig. 1. Heat input model consists of surface and volume heat sources.

and Hashemzadeh et al. [21] in a class as simulation based on finite element methods (FEM), and the challenges and development in great performance computing in computational fluid dynamics are studied by Wang et al. [22], Abderrazak et al. [23], Zhao et al. [24], Tan et al. [25], Courtois et al. [26], Saldi et al. [27], Rohde et al. [28], Gürtler et al. [29], Akbari et al. [30] and Pang et al. [31] in a group; simulation based on finite volume methods (FVM).

There is a strong need for heat transfer measurements and related flow studies, particularly in situations which the definition of fairly straightforward numerical modelling cannot be completely done. This is including, amongst other things, multi-phase flow and various flow conditions. Accurate predictions in the heat transport process modelling are still not refined in particular in flows which need more studies and measurements. Thus, some flow and thermal measurements must be applied to refine the models and to extend numerical methods to compute of temperature, velocity, and also measurement of real material property which gives rise to have reliable and accurate data. This study investigates into the anatomy of micro-welding, such as heat transfer and fluid flow in the thin metal sheet by applying the method of computational fluid dynamics (CFD) using a commercial CFD code, ANSYS® FLUENT software.

2. Methodology

2.1. Governing equations

In this study, the mathematical system of partial differential equations (PDEs) for a detailed general-purpose model of heat transfer and fluid flow through the governed equations of mass conservation, momentum and energy in three-dimensions and also thermodynamic equations of state, and Newtonian model of the viscous stress resulting in Navier–Stokes equations are developed. The divergence or conservative form of the equation system that governs the time dependent fluid flow and heat transfer in three-dimensions of compressible Newtonian fluid have been quoted as follows:

$$\text{Continuity}: \quad \frac{\partial \rho}{\partial t} + \text{div}(\rho U) = 0 \tag{1}$$

Table 1
Laser parameters and welding conditions.

Case	1	2	3	4	5	6
Laser power (P, W)	20	30	40	20	40	60
Scanning velocity (v, m/s)	1.0	1.5	2.0	0.5	1.0	1.5
Spot diameter (d, µm)	17.5	17.5	17.5	35.0	35.0	35.0

$$\text{x-momentum}: \quad \frac{\partial(\rho u)}{\partial t} + \text{div}(\rho u U) = -\frac{\partial p}{\partial x} + \text{div}(\mu\ \text{grad}\ u) + S_{Mx} \tag{2}$$

$$\text{y-momentum}: \quad \frac{\partial(\rho v)}{\partial t} + \text{div}(\rho v U) = -\frac{\partial p}{\partial y} + \text{div}(\mu\ \text{grad}\ v) + S_{My} \tag{3}$$

$$\text{z-momentum}: \quad \frac{\partial(\rho w)}{\partial t} + \text{div}(\rho w U) = -\frac{\partial p}{\partial z} + \text{div}(\mu\ \text{grad}\ w) + S_{Mz} \tag{4}$$

$$\text{Energy}: \quad \frac{\partial(\rho i)}{\partial t} + \text{div}(\rho i U) = -p\ \text{div}\ U + \text{div}(k\ \text{grad}\ T) + \Phi + S_i. \tag{5}$$

Equations of state:

$$p = p(\rho,\ T) \text{ and } i = i(\rho,\ T) \tag{6}$$

$$p = \rho R T \text{ and } i = C_v T \quad \text{(e.g. perfect gas)}. \tag{7}$$

The detailed information about governing equations is available [32] and is not repeated here.

2.2. Heat source modelling

By reviewing the literature (Mazumder and Steen [33], Zacharia et al. [34,35], Sonti and Amateau [36], Shanmugam et al. [20] and Ismail [3]), it can be observed that the reported values of the heat distribution factor in the volume term vary significantly but are mostly similar in the surface. The present work has defined and adapted an improved approach for moving heat sources by writing a specific UDF (User-Defined Functions) to perceive continuous laser welding process and applied in both surface and volumetric heat sources as heat flux on top and convection within the weld pool respectively, whereas the weld pool size grows through the framework. Thus, the heat inputs on the top surface and around the molten pool were assumed to have the following adaption Gaussian distributions respectively:

$$Q_S = \frac{f P_S}{\pi {r_d}^2} \exp\left(-3\frac{r^2}{{r_d}^2}\right) \tag{8}$$

$$Q_V = \frac{f P_V}{\pi {r_d}^2 h_d} \exp\left(-3\frac{r^2}{{r_d}^2}\right)\left(1 - \frac{z}{h_d}\right) \tag{9}$$

where f is the factor of heat distribution that influences the power distribution, P_S and P_V are the laser power absorptions in terms of surface and