Journal of Manufacturing Processes 16 (2014) 264–275

Contents lists available at ScienceDirect

Journal of Manufacturing Processes

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

Influence of displacement constraints in thermomechanical analysis of laser micro-spot welding process

R.S. Desai, S. Bag*

Department of Mechanical Engineering, Indian Institute of Technology Guwahati, Guwahati 781 039 Assam, India

ARTICLE INFO

Article history:
Received 22 June 2013
Received in revised form 6 October 2013
Accepted 7 October 2013
Available online 15 November 2013

Keywords:
Residual stress
Laser welding
Microjoining
Finite element method
Heat transfer

ABSTRACT

The evolution of mechanical components into smaller size generating a need for microwelding of these components using laser which offers better control as compared to arc and plasma processing. The present article describes the numerical simulation of laser micro-spot welding using finite element method. A two dimensional Gaussian distributed surface heat flux as a function of time is used to perform a sequentially coupled thermal and mechanical analysis. The model is used for simulating laser micro-spot welding of stainless steel sheet under different power conditions and configurations of mechanical constraints. The temperature dependent physical properties of SS304 have been considered for the simulation and an isotropic strain hardening model has been used. The simulated weld bead dimensions have been compared with experimental results and temperature profiles have been calculated. The maximum deformation of 0.02 mm is obtained with maximum laser power of 75 W. The thermal stress is more inducing factor to temperature induced residual stresses and plastic strain as compared to mechanical constraints. The plastic strain changes significantly by displacement constraints as compared to residual stress.

Introduction

Material joining, whether at macro, micro, or nano scale is an essential and important aspect of manufacturing and assembly. Laser processing offers unique advantages over other microfabrication techniques on account of its versatility, better control, rapid fabrication, and excellent mechanical properties. Hence it is imperative to study the laser microwelding process in greater detail. Microwelding can be defined as the process where at least one dimension of the part being processed is less than 100 μm [1]. Laser microjoining are processed at high operating speeds in a non-contact mode of operation and selective energy concentration. The process leaves a small HAZ with low distortion and excellent metallurgical properties. Naturally laser microwelding process has a great number of applications which include microelectronic components, bio-medical implants, sensors, packaging, lightweight automotive structures etc. Conduction mode is normally used for welding of foils and thin sheets whereas keyhole mode is used for much thicker sections [2]. However, the ability of a laser to produce desired results greatly depends upon several laser parameters and their interdependence. The typical process parameters for laser welding are pulse energy, power density, energy distribution in the beam, pulse duration and frequency, peak power and spot size.

A wide variety of laser beam sources are used for micro joining processes, each having its unique advantages and disadvantages. The Nd:YAG laser of adequate beam quality has been the choice for a long period of time for microwelding. The YAG lasers have a wavelength of 1.064 μm which is exactly ten times smaller than CO_2 lasers hence can be used for producing very small spots and it works efficiently on metals but their wavelengths are not easily absorbed by many other organic materials. A CO_2 laser beam has much more latitude and can be absorbed easily by many organic materials and is primarily used in the continuous wave mode. More recent advances include fiber lasers that are solid-state but produce the laser light in the confines of an optical fiber which produce beams of very high beam quality and thus can be focused down to a very small spot size. Another recent development is the direct diode laser where light from a bank of laser diodes is directly used for welding. Diode lasers are characterised by their ability to be focussed into very fine spot on account of their small wavelength of 800–976 nm. They can be used very efficiently for the welding of plastic materials.

Naeem [3] provides a comparison between pulsed Nd:YAG and single mode fibre lasers for stainless steels and more reflective materials like aluminium and titanium. At a low power level of 100 W, fiber lasers can be employed for micro welding of steel sheets but not for reflective materials. Pulsed Nd:YAG laser is able to weld the reflective materials at low average power [4–6].

---

* Corresponding author. Tel.: +91 361258 2686.
E-mail addresses: swarupbag@iitg.ernet.in, taswarup@gmail.com (S. Bag).

1526-6125/$ – see front matter © 2013 The Society of Manufacturing Engineers. Published by Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.jmapro.2013.10.002

Ventrella et al. [7] carried out seam welding for stainless steel foil using pulsed Nd:YAG laser by precisely controlling the laser pulse energy. Triantafyllidis et al. [8] investigated the use of diode laser for joining k-type thermocouples. The diode lasers performed well for smaller diameters whereas for larger diameters Nd: YAG processed thermocouples were better. Nobuyuki et al. [9] carried out micro welding of thin stainless steel foils using a direct diode laser. Conduction mode of welding was observed while monitoring the weld bead [10]. Kawahito et al. [11] carried out in-process monitoring of spot microjoining of stainless steel foils using CW fiber lasers [12] and for titanium sheets [13]. Kleine [14,15] observed the usability of fiber lasers in single and pulsed mode for micro joining purposes. The study provided data about the power stability of pulsed fiber lasers and their suitability to process a wide range of materials. Bag [16] summarised the laser conditions corresponding to the joining of metals, non-metals, and dissimilar materials. It is observed that mostly fiber lasers and Nd:YAG lasers have been used for micro joining. The Nd:YAG laser is characterised by long and high energy pulses but poorer beam quality whereas fiber lasers are characterised by high repetition rate with single mode beam quality but low pulse energy. Overall fiber or diode lasers are preferred for smaller size substrate materials whereas Nd:YAG lasers are used for comparatively thicker sections.

The prediction of laser welding behaviour is an important aspect as the thermal analysis of the joint constitutes an essential prerequisite for designing the process parameters as well as the mechanical attributes of the joint. Hence, for an accurate prediction of the behaviour a very precise mathematical description of the heat source is essential. A great amount of research has been conducted for the development of such models. Rosenthal [17] and later Rykalin [18] developed the first mathematical models to describe the heat source in welding. Later on several distributed heat source models using Gaussian distribution has come out [19]. Zacharia et al. [20] developed a 2D finite difference model using a Gaussian heat flux equation to describe the convective flow and heat transfer in the fusion zone during laser welding. Friendman [21], Krutz and Segerlind extended the Pavelic model for a moving heat source. Goldak et al. [22] proposed more realistic models by assuming a semi or a double ellipsoidal profile. Mazumder and Steen [23] proposed the first model to describe the continuous laser welding process numerically. The model implemented finite difference technique for a Gaussian distribution and started with the assumption that energy absorption followed Beer-Lambert law. Chang et al. [24] proposed the variation laser heat source model for joining thin sheets.

Most researchers consider the classic Fourier heat conduction for heat transfer analysis in laser microwelding. Balasubramanian et al. [25] have numerically modeled the laser beam welding process for joining stainless steel. Yibas et al. [26] studied the laser welding of mild steel sheets of thickness 2 mm. Temperature and stress fields are computed in the welding region through the finite element method. The residual stress developed in the welding region agreed well with the XRD results. The metallurgical and residual stress evaluation of CO_2 laser welded super-austenitic stainless steel is carried out by Zambon et al. [27]. It is observed that the residual stress is tensile and close to the yielding strength of the substrate material in the longitudinal direction in the weld bead while the stresses are compressive in the transverse direction in the base material. Martinson et al. [28] conducted experimental and numerical studies of 2 mm thickness that were spot welded with different configurations. It was found out that the weld region in laser spot welding is surrounded by a compressive region which has higher compressive stress values and larger size than that of resistance spot welds. Wang et al. [29] developed a finite element model to study temperature fields and molten pool shapes during continuous laser keyhole welding. Melting and evaporation enthalpy, recoil pressure, surface tension, and energy loss due to evaporating materials were considered in this model. Trivedi et al. [30] conducted thermo-mechanical analysis for laser spot welding.

Laser microjoining is a complicated process involving several aspects such as the laser material interactions, heat conduction, and loss, material flow, and changes in the thermo-mechanical properties. Experiments conducted to study these aspects are generally costly and complicated. Finite element modelling is used to predict the weld behaviour to a great degree of accuracy by considering the above mentioned phenomenon. Literature indicates that studies directed towards laser micro-joining have predominantly been experimental in nature. However, there are several finite element models that study the conventional laser welding process. These models can be extended to model the laser micro-spot welding. The focus of the current study is the development of a finite element model that accurately describes the laser micro-spot welding process. The primary objective of the current study is the evaluation of the resultant welding residual stresses in transverse, longitudinal and thickness direction from the weld bead location and to investigate the effect of mechanical constraints on residual stress and strain.

A few basic assumptions are made for the formulation of the finite element model. The laser source is assumed to be continuous wave fiber laser with efficiency of 40%. The laser radiation is directly incident on the surface of the sheet with a beam diameter of 50 μm. The material to be welded is SS 304 and all the thermo-mechanical properties have been considered as temperature dependent [31,32]. The latent heat of fusion has been considered by adjusting the liquid specific heat between the solidus and the liquidus temperature. Both the laser source and the work piece are stationary. There is no mesh movement during the simulation. As keyhole formation is not expected, the energy absorption of the plasma can be neglected. There is no internal heat generation during welding. As the laser is applied for a very short period of time, the heating and solidification take place rapidly. Hence the convective redistribution of heat within the weld pool is neglected [33]. For mechanical analysis, the sheet material is assumed to follow the bi-linear isotropic hardening law [34].

Theoretical formulation

In fusion welding, the heat generated by plastic deformation is very less than that generated by the heat source during welding. Therefore, a sequential thermal and mechanical numerical analysis can be applied; i.e. the mechanical analysis depends on the calculated thermal field but not vice versa. The approach of dividing the thermo-mechanical calculation into two steps is the most frequently adopted, and this is also the procedure applied in the present work. The basis of the sequential thermo-mechanical analysis is as follows. At first, the thermal analysis is carried out to calculate the time-temperature distribution in a non-linear heat transfer analysis. The heat input into the work piece is approximated by a surface heat source with constant shape.

Based on the basic principles of thermal transfer and conservation of energy, the three dimensional heat conduction equation governing temperature distribution within specimen with heat generation may be expressed as [30]:

$$\rho c_p \frac{\partial T}{\partial t} = \frac{\partial}{\partial x}\left(k_x \frac{\partial T}{\partial x}\right) + \frac{\partial}{\partial y}\left(k_y \frac{\partial T}{\partial y}\right) + \frac{\partial}{\partial z}\left(k_z \frac{\partial T}{\partial z}\right) + Q(x, y, z, t) \tag{1}$$

where ρ is the density, c_P is the specific heat, T is the temperature, t is the time, k is the thermal conductivity, and Q is the heat generation rate. Three types of boundary conditions are applied