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Thermal modelling of laser welding and related processes: a literature review

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Abstract

The main emphasis of this review is on thermal modelling and prediction of laser welding in metals. However as similar techniques are employed to model conventional welding processes such as arc, resistance and friction, as well as related processes such as alloying, cladding and surface hardening, part of this review is given over to the modelling of these processes where appropriate. The time frame of the review is up to the year 2002.

Keywords: Modelling; Simulation; Laser welding; Welding; Surface treatment; Literature review

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1. Introduction

The source material for this review is taken from a Doctoral Thesis entitled *Numerical Simulations of Thermal Processes and Welding* by one of the authors (A.P.M), submitted to the University of Essex, UK, in January 2003. References are therefore included up to the year 2002. One principal outcome of this doctoral work is a flexible thermal modelling code named TS4D[1] (Thermal Simulation in 4 Dimensions, there being 3 spatial dimensions + time). It is the culmination of modelling expertise at Essex University over a period of more than a decade by the team supervised by Professors Phiroze Kapadia and John Dowden. TS4D can handle multiple sources in both surface and volume format, surface sinks, multiple material workpieces, a variety of surface cooling mechanisms, and produces both steady state and time-dependent predictions.

Although the main emphasis of this review is on prediction of laser welding in metals, similar techniques are employed to model conventional welding processes such as arc, resistance and friction, as well as alloying, cladding and surface hardening. Indeed modellers in one field tend to publish in the other fields as well, so part of this review is given over to related processes where appropriate.

Laser keyhole welding is often referred to as a high energy density or power beam technique. The fact that absorption of a laser beam increases with temperature has enabled the use of the laser beam as a practical heat source for welding. For a CO_2 laser, the absorptivity of carbon steel [1] varies from 4% at room temperature to more than 30% at melting temperature and reaches about 90% at vaporising temperature.

For all laser welding irrespective of the type of laser employed, energy is absorbed at the surface of the metal in a layer only a few nanometres thick by a process known as Fresnel Absorption. If the intensity is high enough, vaporisation occurs with some of the metal electrons becoming free (ionisation). These free electrons then absorb energy directly from the beam by a process known as inverse Bremsstrahlung. This results in higher temperatures, increased ionisation and increased absorption leading to vaporisation of the surface which forms a small depression in the workpiece. As the depression deepens, a keyhole forms and the laser light is scattered repeatedly within it, so that Fresnel Absorption occurs at the keyhole walls too, thus increasing the coupling of laser energy into the workpiece. As the keyhole develops, the power of the source can now be absorbed at greater depths, not just at

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[1] Details of TS4D can be found on the Abington Consultants website *abingtonconsultants.co.uk*.

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the surface. Some absorption or scattering of the power also occurs in the plasma vapour within the keyhole that can emerge as a plume which can obstruct or defocus the beam (especially with CO_2 lasers). However, the plume can also radiate energy back to the specimen. While the laser energy is applied, surface tension and gravitational forces have the effect of closing the keyhole whereas vapour pressure and ablation help keep it open. Laser welding is usually realised at speeds much higher than conventional processes.

All the references discussed in this review are based on solutions of the heat conduction equation. The analytical solutions on which most models have been based are described in Conduction of Heat in Solids by Carslaw and Jaeger [2]. This contains a collection of solutions for most simple geometries and shapes of heat source, both steady state and time-dependent. Readers interested in the mathematics and solution methods are referred to this work.

2. Basic analytic solutions

2.1. *Moving point source in a medium of infinite thickness*

Rosenthal [3] published one of the earliest analytic solutions applicable to welding. He considered a point source incident on, and moving relative to, an infinite material. His solution simulates surface melt runs relating to conduction welding. The solution can be rendered finite in depth and width (assuming the source moves along the length of the material) by using the method of images. Since he did not account for the finite area of a real source, it is inaccurate in the region where the point source is incident.

2.2. *Moving line source in an infinite or semi-infinite material*

Rosenthal also derived the solution for an infinite line source extending through the depth of the material, its axis perpendicular to the top and bottom surfaces. This 2-D solution simulates full penetration welding of sheets of any thickness and can also be applied to conduction, or nonfully penetrating welding of thicker sheets provided the length scale (the thermal diffusivity divided by the processing speed) is large enough. For aluminium this value is ~ 6 mm and for steel it is ~ 0.6 mm. A recurring problem with such point and line source models is that they lead to infinite temperatures at the source.

With these solutions, Rosenthal produced an approximate single formula capable of predicting the time and rate of cooling for a wide variety of thicknesses of steel, and for ranges of temperature and welding conditions. For both high- and low-processing speeds, Swift-Hook and Gick [4] approximated Rosenthal's solution and predicted that the proportion of power needed to cause melting as a function of the incident power reaches a maximum of 48%.

On the subject of laser cutting, Bunting and Cornfield [5] obtained a solution due to a cylindrical beam by integrating the line source solution over the area of a circle from which they were able to evaluate the cut speed (i.e. translation speed) as a function of the incident power per unit thickness. They found that the efficiency of the cutting process could be maximised for a certain power density and cut speed, depending on the jet diameter. Their results, other than in a few cases, were quite different from those found experimentally, but fared no worse than the listed results of other authors.

A review of mathematical models of laser cutting of steels has been presented by O'Neill and Steen [6].

2.3. *Continuous Gaussian surface source in an infinite solid*

By integrating point and line source solutions over an area it is possible to calculate the heating from top-hat, Gaussian and cylindrical sources, etc. Lax [7] studied the steady-state temperature distribution due to a stationary Gaussian beam in a semi-infinite cylindrical medium, while Nissim et al. [8] presented a 3-D solution for a moving elliptical Gaussian heat source. For the case of silicon and gallium arsenide they also incorporated formulae for a varying thermal conductivity. Their model was generalised by a numerical algorithm by Moody and Hendel [9].

Miyazaki and Giedt [10] solved the heat conduction equation for a cylindrical molten region having an elliptical cross-section.

Davis et al. [11] considered laser transformation hardening of En8 steel under the influence of a Gaussian surface source. Ignoring surface melting and also the heat of transition required to convert pearlite to austenite, they calculated the depth at which hardening occurs and an estimation of the power required.

2.4. *Moving hypersurface line source for a medium of semi-infinite thickness*

In order to avoid the infinite temperatures produced by a point source or line source, Ashby and Shercliff [12], with reference to transformation hardening, derived a solution (as a development of the Ashby–Easterling hyper point source model [13] for high processing speeds, by representing the heat input as a finite line source situated above and parallel to the surface with its axis lying along the width of the specimen. Since it was not finite along the direction of motion, it was positioned above the surface to avoid the infinite temperatures generated where the beam impinges. They also derived the beam energy required to cause melting.

2.5. *Combined moving point/line sources*

The point and line source solutions of Rosenthal can simulate simple conduction welding and keyhole welding,