Three-Dimensional Heat Transfer Modeling of Laser Beam Welding using Adaptive Volumetric Heat Source and GA based Optimization of Absorption Coefficient

(Winner of HD Govondraj Memorial Research Award in NWS 09 - Mumbai)

S. Bag and A. De
[1]Mechanical Engineering Department, IIT Bombay, Powai, 400076, India (amit@iitb.ac.in)

ABSTRACT

An accurate estimation of the temperature field in weld pool and its surrounding area is important for a priori determination of the weld pool and heat affected zone dimensions, and the weld thermal cycle. The present work reports a finite element based three-dimensional quasi-steady heat transfer analysis for prediction of temperature field and weld dimensions in laser welding process. The novel feature introduced in the model is that a volumetric heat source term is used to account for the energy absorbed by the molten weld pool. However, the volumetric heat source is defined in an adaptive manner by mapping it with the computed weld pool dimensions such that there is no need to predefine the heat source dimensions. The heat transfer model further considers temperature dependent material properties and the latent heat of melting and solidification. The numerical heat transfer model is further integrated with a genetic algorithm (GA) based optimization tool to optimize the value of absorption coefficient that is usually not known with confidence and required to calculate the net heat input into the workpiece. The predicted weld pool dimensions from the overall integrated model are validated successfully against similar experimentally measured results reported in independent literatures for laser beam welding process.

Key words: Laser welding, Heat transfer model, Adaptive volumetric heat source, Genetic algorithm

INTRODUCTION

Laser welding involves the application of a focused laser beam on the workpiece leading to a small weld pool with high depth to width ratio and reduced heat affected zone. The thermal distortion and residual stress are also reduced due to the smaller size of weld pool [1, 2]. Real-time measurement of high peak temperature and steep thermal cycles experienced by the weld pool in laser welding is difficult. A-priori information of the temperature distribution in workpiece is, however, required to estimate the weld dimensions for a given welding condition. Accurate knowledge of peak temperature and weld thermal cycle can also help to estimate the weld microstructure and the corresponding mechanical properties [3-8]. Theoretical modeling of laser welding process is increasingly considered as an effective route for the estimation of weld pool dimensions and weld thermal cycle. A number of researchers developed heat transfer analysis of laser beam welding process either analytically [9-13] or using numerical methods such as finite element or finite difference or finite volume methods [14-17]. The analytical solutions were restricted by the assumption of laser beam as a point heat source and temperature independent material properties. Also, analytical solutions usually assume a semi-infinite workpiece with simple shape while in real situation, the workpiece confirms to finite size and often to complex geometry. An attempt to numerically model laser welding process was reported by Mazumder et al. [14] and thereafter by a number of researchers [15-17]. These models vary widely in several ways e.g. the representation of the laser beam as a heat source, the consideration of material properties and latent heat and in particular, the assumed values of absorption coefficient that defines the amount of net heat input into the workpiece for a given laser power.

A number of researchers [18-22] have also developed convective heat transport based numerical models by solving conservation of mass, momentum and energy equations. Although those models are successful for prediction of temperature field, they are computationally expensive and contain a number of empirical constants that cannot be specified by scientific principle alone. Moreover, the effect of convective heat transport during laser welding of thin metallic sheets can be conceived to be lesser due to smaller weld pool size and rapid solidification. It is subsequently reported that the conduction heat transfer based models using volumetric heat source can also account for heat transport in weld pool to a certain extent that is otherwise included in convective transport based models by virtue of their approach [23-25].

A linear welding process, where the laser beam moves continuously with respect to the workpiece, can be modeled by considering the beam at different positions at successive instants of time and calculating the transient temperature field at each time instant. This approach demands high computational time and space. Alternately, a pseudo-steady approach can be adopted by assuming that the temperature profile around the beam will not change with time when looked from the center of the beam. The pseudo-steady model of linear welding involves the transformation of time coordinate in the governing heat conduction equation into a suitable space coordinate. Thus, a single step analysis can be performed for the entire weld run and the transient temperature field at different instants of time can be easily extracted from the pseudo-steady temperature solution. Such an approach is followed in the present work. The laser beam is considered to be a surface heat source with a Gaussian distribution of heat flux. In addition, it is conceived that as a weld pool will be created, the same will absorb a greater amount of beam energy since the weld pool will be at a higher temperature than the initial incident top surface. A volumetric heat source is considered next that adapts its size and shape from the computed weld pool dimensions.

Furthermore, the accurate values of absorption coefficient are required to calculate the actual heat input into workpiece. The values of absorption coefficient depend on a number of physical features such as peak temperature, surface condition, type of laser beam and workpiece material and so on. For all practical purpose, a single, time-averaged value of absorption coefficient is of demand since the same will allow an accurate estimate of heat input into the workpiece. Traditionally, such unknown input variables are obtained by doing tedious trial-and-error numerical experiments. Alternately, an optimization tool can be integrated with the numerical heat transfer model that inherently identifies the most suitable values of such unknown input parameters based on a small set of known database consisting of measured values of weld dimensions and associated welding conditions. Though classical gradient based optimization techniques [26-28] are powerful tools to find an optimum set of unknown parameters, it can easily get trapped in local minima. Stochastic optimization techniques are capable of finding the global minima by avoiding the local minima [29-35]. In the present work, a genetic algorithm (GA) based optimization tool is adopted to find the optimum values of absorption coefficient.

THEORETICAL MODEL

The governing heat conduction equation in 3D Cartesian coordinate system can be written as

$$\frac{\partial}{\partial x}\left(k\frac{\partial T}{\partial x}\right)+\frac{\partial}{\partial y}\left(k\frac{\partial T}{\partial y}\right)+\frac{\partial}{\partial z}\left(k\frac{\partial T}{\partial z}\right)+\dot{Q}=\rho C_p\frac{\partial T}{\partial t} \quad \text{... (1)}$$

where ρ, C_p and k refer respectively to density, specific heat and thermal conductivity of the work piece material; T the temperature variable, T, as a function of spatial (x, y, z) and temporal (t) coordinates. Considering that the laser beam moves with a constant velocity (u) in y-direction, a moving coordinate system (x, ξ, z) is defined as ξ = y-ut. At any time instant, t, 'ut' is the distance between the laser beam center and the origin of the fixed coordinate system (x, y, z) along y-axis. The governing equation (1) can be rewritten in moving coordinate system as

$$\frac{\partial}{\partial x}\left(k\frac{\partial T}{\partial x}\right)+\frac{\partial}{\partial \xi}\left(k\frac{\partial T}{\partial \xi}\right)+\frac{\partial}{\partial z}\left(k\frac{\partial T}{\partial z}\right)+\dot{Q}=-\rho C_p u\frac{\partial T}{\partial \xi} \quad \text{... (2)}$$

A typical butt-joint geometry is assumed for the modeling purpose. Considering the circular symmetry of the focused laser beam on the top surface of the workpiece, the temperature field is calculated using only one of the two plates with the weld joint interface as the symmetry plane. An adiabatic boundary condition is assumed for the face of the plate that confirms to the weld interface. Part of the top surface, which is under the laser beam, is subjected to a specified heat flux q_s given as

$$q_s=\frac{P\eta_{gau}d}{\pi r_{eff}^2}\exp\left(-\frac{d\cdot x^2}{r_{eff}^2}-\frac{d\cdot\xi^2}{r_{eff}^2}\right) \quad \text{.... (3)}$$

where P refers to the laser power, η_{gau} the absorption coefficient, the effective radius of the focused laser beam on the top surface of the workpiece and d the energy distribution coefficient. As the surface beneath the laser beam melts and a small weld pool forms, an adaptive volumetric heat source term is defined within the weld pool as [23-24]

$$\dot{Q}(x,\xi,z)=\frac{6\sqrt{3}f_{\xi}P\eta_{vol}}{\pi\sqrt{\pi}\ \text{abc}}\exp\left(-\frac{3x^2}{a^2}-\frac{3\xi^2}{b^2}-\frac{3z^2}{c^2}\right)$$

$$\text{where}\quad \left.\begin{aligned} a &= W_l^c \\ b &= \frac{W_w^c}{2} \\ c &= W_p^c \end{aligned}\right\} \qquad \text{.... (4)}$$

where W_l^c , W_w^c and W_p^c represent the computed values of the weld length, weld width and weld depth respectively obtained iteratively from the numerical calculations, and η_{vol} refers to the absorption coefficient of the weld pool volume. The values of W_l^c , W_w^c and W_p^c change as the computed weld pool dimensions change during numerical calculations. Thus, equation (4) does not need a priori knowledge of the final weld pool shape that is otherwise required in similar expressions used earlier [23-24]. The rest of the plate surface is subjected to convective and radiation heat losses with a lumped film heat transfer coefficient, h, which is calculated as $h = 2.4\cdot10^{-3}\cdot\varepsilon\cdot T^{1.61}$ [16].

The solution domain is discretized with isoparametric brick elements with eight nodes with a finer mesh below the heat source and coarser towards the edges in a geometric progression to reduce total number of nodes and elements. Following Galerkin's weighted residue technique in finite element method, the governing equation and the associated boundary conditions are discretized and the final algebraic equation to be solved can be written as

$$[H]\{T\}+[S]\{\dot{T}\}+[\bar{H}]\{T\}+\{F_Q\}+\{F_q\}+\{F_h\}=0 \qquad \text{.... (5)}$$

where the first and second terms refer to heat conduction and heat capacity matrices respectively, the third and the last terms account for convective heat loss, and the fourth and the fifth terms account for input of volumetric heat and surface heat flux respectively. The temperature dependent material properties of SS316 [36] are used for the numerical calculations. The latent heat of melting and solidification is included through an increase or decrease in the specific heat of the material [23-25]. Furthermore, the numerical model requires accurate values of η_{gau} and η_{vol} for reliable calculations. To optimize the values of η_{gau} and η_{vol}, an objective function, O(f), is defined as

$$O(f)=\sum_{m=1}^{M}\left[\frac{(W_p^c)_m-(W_p^{obs})_m}{(W_p^{obs})_m}\right]^2+\sum_{m=1}^{M}\left[\frac{(W_w^c)_m-(W_w^{obs})_m}{(W_w^{obs})_m}\right]^2$$

$$=\sum_{m=1}^{M}[(W_p)_m^*-1]^2+\sum_{m=1}^{M}[(W_w)_m^*-1]^2 \qquad \text{.... (6)}$$

where , $(W_p^c)_m$, $(W_w^c)_m$, $(W_p^{obs})_m$ and $(W_w^{obs})_m$, and refer respectively to the computed values of weld depth and width, and their corresponding measured values for m[th] welding condition. The terms $(W_p)_m^*$ and $(W_w)_m^*$ are non-dimensional and indicate the extent of over or under-prediction of weld depth and width respectively. The term, f, in the objective function corresponds to a set of two unknown parameters as

$$\{f\}=\{f_1 \quad f_2\}=\{\eta_{gau} \quad \eta_{vol}\} \qquad \text{.... (7)}$$

A real number based GA optimization procedure involving a PCX operated G3 model [29] is used to identify the optimum set of uncertain parameters, η_{gau} and η_{vol} corresponding to the minimum value of O(f). The PCX operator creates new individuals, i.e. random sets of η_{gau} and η_{vol}, structured by G3 model. The optimization procedure starts with an initial population of 100 individual data sets that are created randomly where each individual consists of a set of values of η_{gau} and η_{vol}. The values of O(f) are computed for all known welding conditions using each individual and the best individual is decided corresponding to the minimum value of O(f). Two more individuals are selected next randomly from the initial population. From these three individual sets, two new offspring are created subsequently using the PCX operator [29]. Next, O(f) is evaluated for the known welding conditions using the two newly generated offspring. Subsequently, a set of four individuals is created with the two newly generated offspring and randomly selecting two more individuals from the initial population. The four individuals are ranked based on the increasing order of their corresponding values of O(f). The first two individuals in the rank are used to create subsequent offspring (or new individual sets) and also added in the initial population by replacing two existing individuals in a random manner, thereby enriching the initial population with good individuals. The complete process is repeated till the convergence criteria i.e. a specified minimum value of O(f) is achieved. The overall integrated model is developed using INTEL Fortran (ver. 8.1).

RESULTS AND DISCUSSION

The present work considers the laser seam welding of 0.2 mm thick stainless steel (SS316). Table 1 shows the measured weld pool dimensions and the corresponding welding conditions. The experiments were carried out using an Nd:YAG laser beam with focused beam diameter of 0.30 mm [11-12]. The measured weld dimensions and associated welding conditions corresponding to data set indices 2, 6, and 8 (marked as * in table 1) were used to identify the values of η_{gau} and η_{vol}. The measured weld dimensions corresponding to data set indices 1, 3, 4, 5 and 7 remain unknown to the optimization exercise and thereafter, used for the validation of the overall integrated model.

Table 1 Experimentally measured weld dimensions [11-12]

Data set index	Laser power (W)	Weld velocity (mm/s)	Weld depth (mm)	Weld width (mm)
1	40	6.0	0.06	0.20
*2	48	6.0	0.12	0.34
3	52	6.0	over	0.37
4	54	6.0	over	0.40
5	40	8.0	0.04	0.18
*6	50	8.0	0.10	0.30
7	40	10.0	0.02	0.16
*8	60	10.0	0.15	0.39

Figure 1 shows the sensitivity of the computed values of non-dimensional weld depth, $(W_p)^*_m$ and width, $(W_w)^*_m$ with respect to η_{gau} and η_{vol} for all the welding conditions given in table 1. Figures 1(a) and (b) show that corresponding to a fixed value of η_{gau}, the computed values of $(W_p)^*_m$ and $(W_w)^*_m$ increase as η_{vol} increases. It is noteworthy that the values of both $(W_p)^*_m$ and $(W_w)^*_m$ tend to be unity when the computed and the corresponding measured values of weld depth and width will tend to agree. Figures 1(a) and (b) indicate that $(W_p)^*_m$ and $(W_w)^*_m$ tend to be unity when η_{vol} is in the range of 0.45 ~ 0.55. Figures 1(c) and (d) depict that with increase in η_{gau}, the values of $(W_p)^*_m$ and width, $(W_w)^*_m$ increase for a constant value of η_{vol} and both $(W_p)^*_m$ and $(W_w)^*_m$ tend to be unity when η_{gau} is in the range of 0.30 ~ 0.40.

Figures 1(a)-(d) clearly demonstrate that the identification of the optimum and physically meaningful values of η_{gau} and η_{vol}, which can be used as input for the calculation of weld dimensions for only eight welding conditions, is nearly intractable if the same is attempted manually or even graphically. It is therefore necessary to develop a mathematical framework that will learn from the sensitivity of the error in prediction on small changes in η_{gau} and η_{vol} and will lead to an optimum set of these variables. The same is achieved in the present work by interfacing the numerical heat transfer calculation with a GA based optimization algorithm.

Figure 2(a) depicts the randomly generated initial populations, which is the first step of the overall modeling procedure adopted here, distributed over the entire feasible region. Each individual in the population has equal likelihood to be the final solution. Figure 2(b) shows the computed distribution of O(f) corresponding to the initial populations. The multiple peaks in the distribution of O(f) over the complete range of η_{gau} and η_{vol} indicate the existence of a number of local minima each of which corresponds to a candidate solution set for η_{gau} and η_{vol}. Figure 2(b) indicates that the promising solutions exist when $\eta_{vol} > \eta_{gau}$ and within a region encompassed by and $.0.4 \leq \eta_{vol} \leq 0.8$

Figure 2(c) shows the progress in the distribution of computed values of O(f) after third iteration that depicts that the optimum value of η_{gau} and η_{vol} will lie within a region bounded by and . Figure 2(d) shows a global minimum value of O(f) (~ 5.0x10^{-3}), which is smaller than the specified error, is achieved after five iterations corresponding to η_{gau} = 0.34 and η_{vol} = 0.52.

Figure 3 depicts the performance of the overall modeling calculations in terms of the progress of the minimum values of O(f) with the number of iterations. It is observed that the minimum value of O(f) corresponding to the initial populations is nearly 0.115 that decreases rapidly in first two iterations followed by a gentler reduction in O(f) in subsequent iterations.

Figure 4 shows the comparison of the computed values of the weld dimensions and the corresponding measured results for all the eight data sets. The single set of optimum values of η_{gau} and η_{vol} is used for all the computations. Figure 4 indicates a fair agreement between the computed and the corresponding values of weld dimensions including for the data set indices 1, 3, 4, 5 and 7 that are not used during optimization of η_{gau} and η_{vol}. Thus, the optimized values of η_{gau} and η_{vol} are proved to be fairly general for the present set of data sets that covers a wide range of welding conditions. Similar range of absorption coefficients in laser welding were also reported in previous literatures [11-13, 16, 17]. The integrated model linking a Genetic algorithm based optimization algorithm with a numerical heat transfer model is thus proved to be more self-consistent and robust than

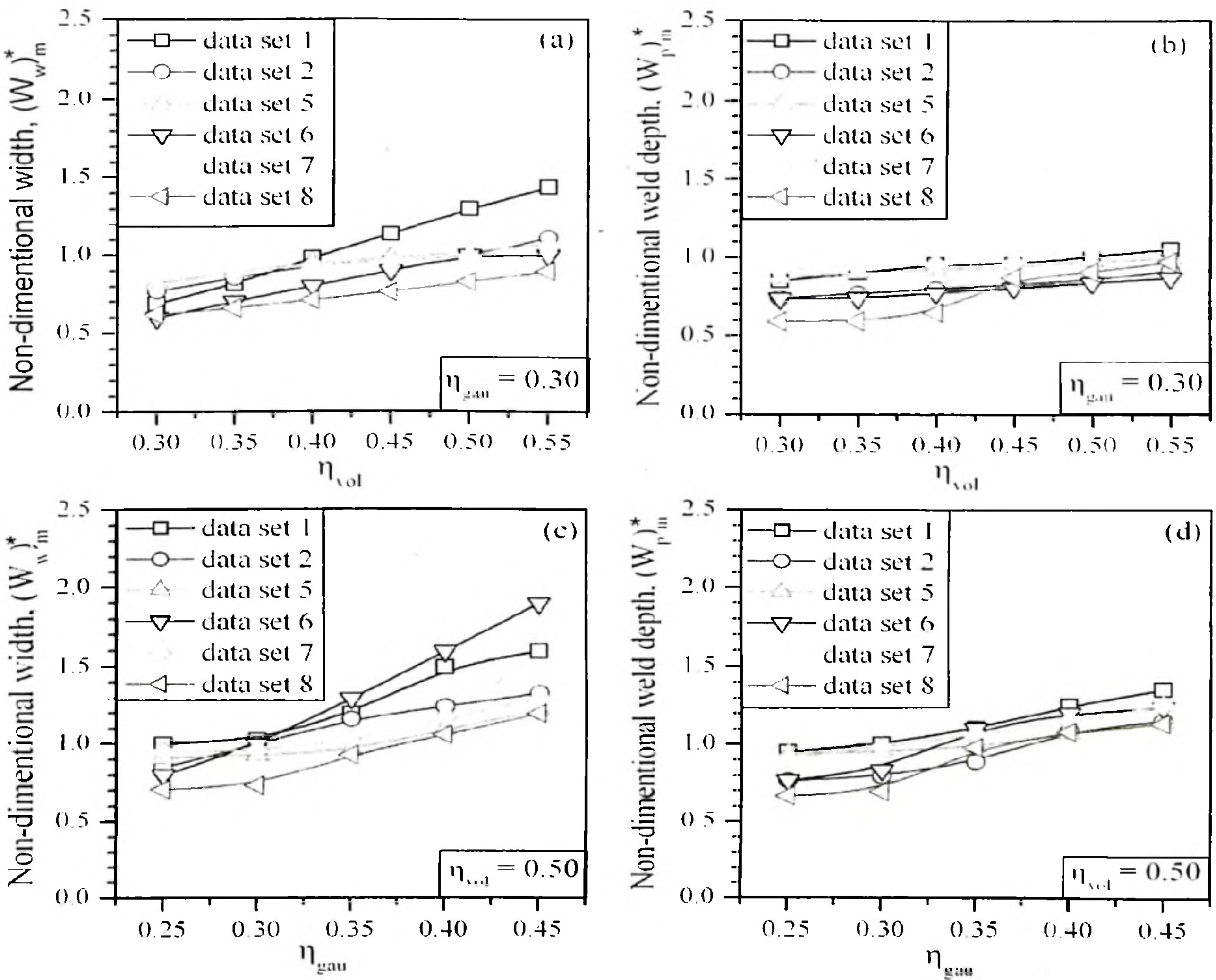

Fig. 1 Influence of η_{gau} and η_{vol} on non-dimensional weld pool dimensions for 6 data sets in table 1

traditional process models in which values of a number of uncertain input parameters are required to fit using trial-and-error numerical experiments.

Figure 5 shows the computed 3D temperature distribution corresponding to a laser power of 50W and weld velocity of 6.0 mm/s. The region heated above 1400°C (marked as red) confirms to the weld pool and its intercepts on x, y and z axes represent the weld length, width and depth respectively. The temperature isotherms are unsymmetrical in the direction of the movement of the laser beam (y-axis). Figure 6 further presents a comparison of the actual weld macrograph and the corresponding computed weld pool profile (along x-z plane) corresponding to a laser power of 48 W and weld velocity of 6.0 mm/s. Figure 6 clearly depicts a fairly reasonable agreement between the computed weld shapes and sizes and the actual weld macrograph reported in independent literature. All the computations are performed using the optimized values of η_{gau} and η_{vol} reported earlier.

CONCLUSIONS

A three-dimensional quasi-steady state numerical heat transfer model is developed using finite element method to analyse heat transfer in linear welding process. To account for greater heat transport in weld pool at high temperature, a volumetric heat source term is introduced that adapts its size according to the size of the weld pool during iterative calculations.

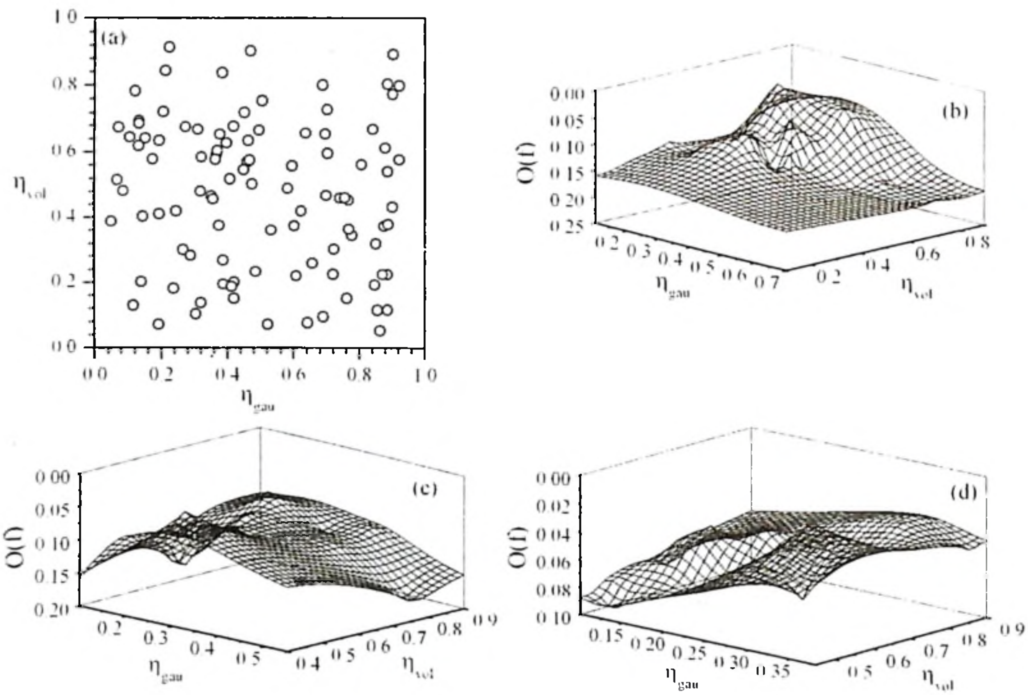

Fig. 2 (a) Initial population of η_{gau} and η_{vol}. Computed distribution of objective function (b) with initial population, (c) after third iteration, and (d) after fifth iteration

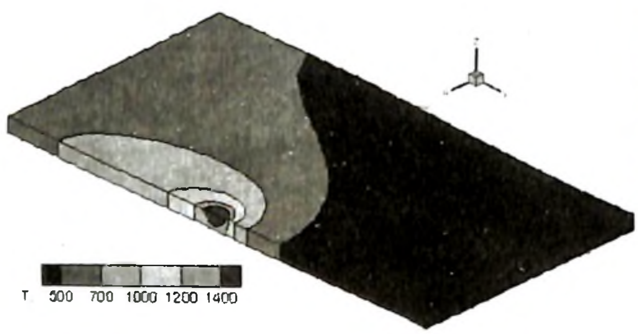

Fig.5 *Computed temperature distribution for a laser power of 50 W and weld velocity 6.0 mm/s*

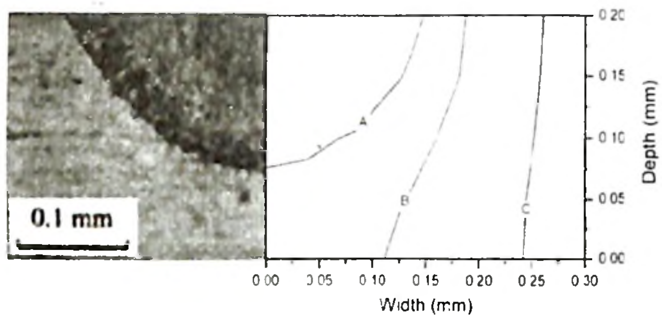

Fig.6 *Comparison of weld macrograph (left side) with computed weld shape (right side) corresponding to a laser power of 48 W and weld velocity of 6.0 mm/s [A – 1400^{0}C, B -1200^{0}C, C - 1000^{0}C].*

Furthermore, the numerical model is integrated with a PCX operated genetic algorithm based stochastic optimization technique to find out the time-averaged, optimum values of absorption coefficient. The overall integrated model is able to identify the optimum values of absorption coefficients from only a few known measurements of weld dimensions and associated welding conditions. Subsequently, the optimized values of the absorption coefficient can be used successfully for the estimation of weld pool dimensions for unknown welding conditions. The integrated model is successfully validated with experimentally measured weld pool dimensions of laser seam welding obtained from independent literatures. This approach can be enhanced further for a priori designing of welding conditions to achieve target weld pool geometry that is being attempted as a part of the present research work.