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A Literature Survey on Modeling of Laser Welding and its Related Processes

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Abstract: *Laser welding and its related processes is a complex phenomenon since it has involving the interaction of Thermal, Mechanical, Electrical and Metallurgical changes. So, modeling of laser welding process is very important for process understanding and time effective. Laser welding process have been modeled by analytical and mathematical methods especially, finite element method and finite difference method, a combination these two methods is an ideology of finite volume method which governs most of the process parameters.This article covers a brief history about modeling of laser beam welding process, modeling of heat conduction and keyhole during laser welding of different materials including some studies on heat and mass transfer during laser welding.*

I. Introduction

The availability of lasers as a source of Thermal energy has led to their use in a variety of situations in many diverse fields, such as laser material process and laser welding. The features of lasers are very suitable for automated processes. The absorbed power level of laser can be estimated fairly accurately means that the effects of the thermal input, both the desired ones and the undesirable side-effects, in principle those can be estimated relatively and accurately. This is another advantage in work, where precision is important and is a principle reason, why thermal modeling is valuable but it has many aspects? It can be used to analyze situations where undesirable side-effects are discovered or to save development time by means of elaborate computational models that have been shown to be capable of producing accurate numerical agreement with the results of earlier experiments (JohnMichaelDowden, 2001). Hence, modeling of laser welding process is very important for process understanding as it is possible to simulate different process, material and relative parameters before the actual manufacturing in an industry.

II. Brief History About Modeling of Laser Welding

Rosenthal (1946) and others, have studied classical solutions for the heat conduction equations and then Carslaw and Jaeger (1959) have brought those heat conduction equations in a complete reference book for analytical solutions. The heat sources are considered as point source, line source and plane sources, since these are the only types of geometry were analytical solutions are straightforward to obtain. Based on this, studies on the laser welding process begin in the early 1970's and several mathematical models have been developed as on date. The heat sources mentioned earlier are suitable to predict the thermal history at a large distance from the source. A model was developed to estimate the temperature contours as function of time during pulsed laser welding in addition to the measurement of fusion zone and heat affected zone (M.R.Frevin, 1999). The compilation and discussion on many heat transfer models until the year 2002 that are developed for various processes including laser welding (A.P. Mackwood, 2005). An analytical and the numerical model effectively used to calculate the temperature distribution in a semi-infinite medium for a localised moving 3D heat source of any type for use in laser material processing, welding and layered manufacturing (M.Van Elsen, 2007). A bibliography that provides hundreds of references until from the year 1976 to 2004 on modelling and analysis of laser beam welding of 2D, 3D thermomechanical, to evaluate temperature, stress and distortion distributions, linear and non-linear analysis, phase change problems, solidification, melting, austenitic-martensitic phase change, martensitic transformation, solid liquid phase transformation etc., including welding under consideration of austenitic stainless steel and other metals and alloys (Mackerle, 2004).

Beside, many commercial software also have been developed and simulated for variety of materials processing applications based on finite element method and finite volume method for instance, ABACUS software (R.Spina, 2007), (B.Carmignani, 2001), SYSWELD code (S.A.Tsirkas, 2003), (C.Hackmair, 2003), (S.K.Bate, 2009), FORTRAN software (Michael Davis, 1985), SYSTUS FE code (J.B.Leblond, 1989), GRID code PHOENICS (C.Prakash, 1987), MAPLE software (Gustav Amberg, 1999), ADINAT (A.Strauss, 1989), ALBERTA (J.Montalvo-Urquizo, 2009) and FLUENT software (Shanping Lu, 2008).

Newly developed models that are capable for simulating many aspects of laser welding, for instance, during beam welding including keyhole oscillations or melt pool respectively vapour flow using software package open FOAM, temperature distribution (K.SureshKumar, 2016), electromagnetic wave propagation and the thermo mechanical processes are obtained with COSMOL multiphysics code (Andreas Otto, 2010). The new code called LUMET (for Laser Ultrasonic Metallurgy, provides unprecedented capabilities by allowing observation of internal physical state of the specimen during Gleeble tests, with LUMET, researcher can measure the texture of the sample, Grain size and growth temperature of the austenite phase in steels (D.Ferguson, 2009).There are many codes that are developed by researchers and commercial software packages are being made to model the complicated welding process as simple.

III. Modeling of Heat Conduction of Laser Welding

The laser-metal interaction is very complex phenomenon with multi-dimensional, multi parameter. During the laser-metal interaction the mechanism of energy absorption in to heat transfer through work piece has been studied so far considering the important parameters related to laser, thermal and mechanical properties of the work piece, material structure and chemical composition (M.Kermal Apalak, 2003). Therefore, a clear understanding of these conditions is essential in improving the efficiency of the laser welding process.

An analytical solution of heat conduction model was developed, to consider the laser absorption in one material as well as at interface to achieve the results in terms of temperature distribution, thermal flaw (Zimmer, 2009). A 3D heat conduction model was used to obtain the temperature variation of the base metal in Nd: YAG laser and gas tungsten arc hybrid welding. Temperature distribution of laser beam and Tungsten are and hybrid sources are obtained for comparison (Y.T.Cho, 2011).Some studies about temperature distribution on ceramic, mullite and austenitic stainless steel materials of laser assisted turning and milling (S.Sun, 2010). Three dimensional finite element simulation of laser welding of copper (L.E.Lindgren, 1997), thick steel plate (C.Carmignani, 1999), low carbon sheet (P.Martinson, 2009), AISI 410 stainless steel with brass coating (Liang Liu, 2011), dissimilar welding of AISI 316 stainless steel and low carbon steel (E.M.Anawa, 2008) and multilayer laser powder deposition of AISI 420 stainless steel (L.Coasta, 2005) are simulated and predicted.

Fluid flow and heat transfer in the weld pools for the GMAW were investigated theoretically through a transient axis symmetrical solution of the Navier stokes equation and the equation of conservation of energy. The computation incorporates electromagnetic, buoyancy, surface tension and drag forces and molten metal droplets. The simulation was executed with PHOENICS code (I.S.Kim, 1998). A three dimensional analytical model of the Fourier heat equations developed for laser-material interaction in homogeneous media which includes spatial and temporal dependence of laser source and the geometry of the sample (Mihai Oane, 2008). A control volume method approach was introduced to discretize the governing equation of heat transfer of materials like Stainless steel, Titanium, Tantalum, Nickel and Aluminium for laser heating of semi-infinite solid with consecutive pulses. Influence of material properties on temperature filed was investigated (S.Z. Shuja, 2008)**.**Physical simulation has developed in to extremely useful and available tool used to study many metallurgical processes, develop new materials and obtain characteristics of materials in real world situations. Several analytical and numerical models have been proposed to understand the temperature fields, weld pool geometry, keyhole profile, temperature and stress distribution, mechanical behaviours and distortions as shown in welding simulation procedure Fig. (G.A. Moraitis, 2008).

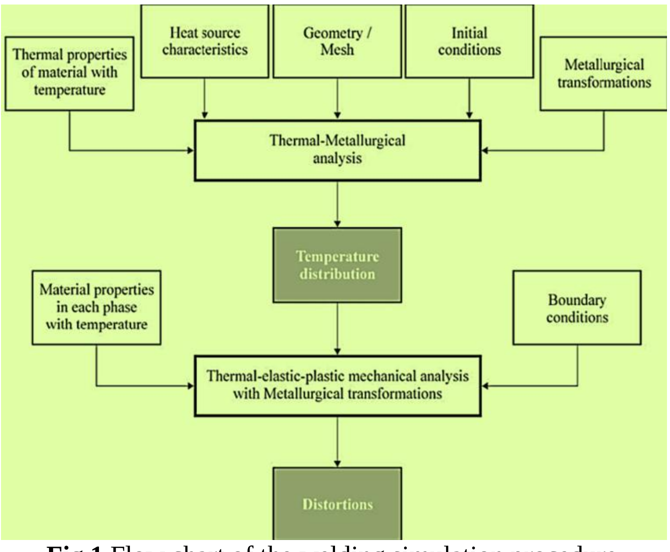
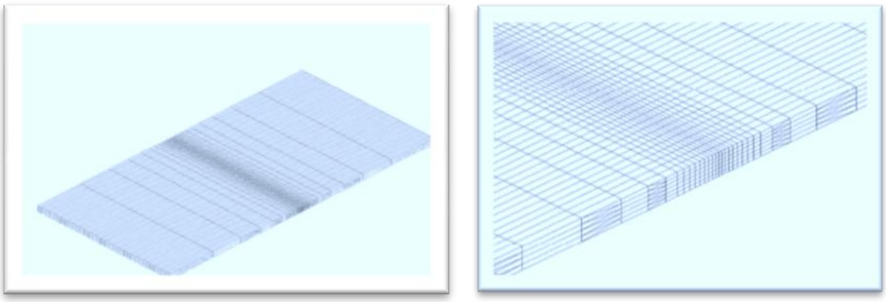


Fig.1 Flow chart of the welding simulation procedure

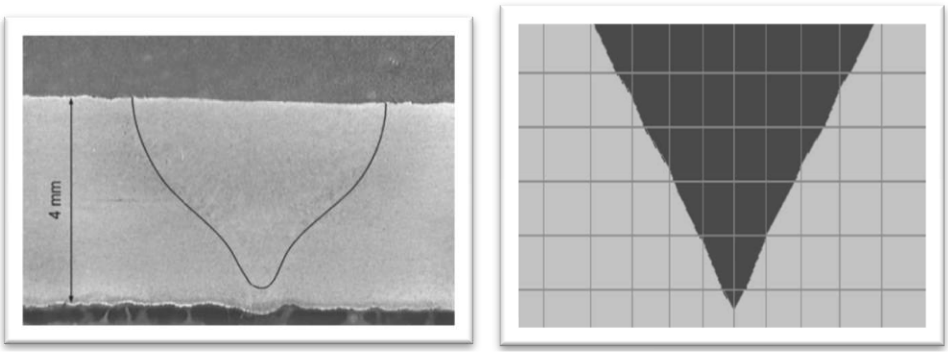
A computational model was developed in order to simulate any laser induced surface modification process with or without the kinetics condition, concludes that kinetic condition for laser annealing, machining and pulsed laser deposition (PLD) (J.S.Kapat, 1998). Finite volume methods applied to employ the welding phenomena with regard to the computational fluid dynamics (CFD) for the weld pool fluid dynamics, heat transfer and phase change (Gareth A.Tayler, 2002). The application of the FEM to predict the thermal and mechanical effects of welding was described: computational welding mechanics (CWM). The most important modelling issues are the heat input and material behaviour. The use of more physical based model for material behaviour and it's relation to the micro structure as well as evaluation equations for the micro structure are expected to improve the predictive capability in CWM (Lindgren, 2006). Material data is a vital for computed aided engineering (CAE) process simulation packages based on finite element (FE) or finite difference (FD) analysis. Such data including physical, thermo-physical mechanical properties are as function of temperature (Z.Guo, 2009). A 3D finite element model was developed to simulate a non-linear heat transfer model, based on keyhole and a coupled transient thermo mechanical analysis using SYSWELD FE code for the butt joint specimens of steel as shown in

Fig. and 3 (S.A.Tsirkas, 2003). A 3D finite element model was developed and simulated with ABACUS software to laser welding process of AA5083 thin sheets and predicted their final distortions (R.Spina, 2007).



(a) (b)

Fig. 2 (a) FEA meshes modelling of weld sample and (b) the weld area



(a) (b)

Fig. 3 Welds pool from (a) experimental investigation and (b) FE simulation

ANSYS code another important package that solves for the combined effects of multiple forces, accurately modelling combined behaviours resulting from 'multi physics' interactions. The software also features advanced nonlinear material simulation. Using ANSYS software many number of analytical and numerical models of welding processes have been developed to the modified heat source model (Komeil Kazemi, 2009), (Hwa Teng Lee, 2010), to predict the weld cross section in deep penetration laser welding and model power absorbed in the keyhole and in the surface (Jamshid Sabbaghzadeh, 2008), to evaluate temperature, residual stress and distortion distributions during the welding process of structural components such as of austenitic stainless steel, (K.R. Balasubramanian, 2010), Alloy 690 (Hwa Teng Lee, 2010),low carbon steel plate (B.S.Yilbas, 2010), tensile residual stress of spot welded of AISI 304 SS (B.W.Cha, 2003), DH36 steel plates (G.A. Moraitis, 2008), steel and aluminium (G.A.Moraitis, 2009), Zinc coated steel sheets (A.Loredo, 2002),to reduce the possibility of fracture in the process of cutting glass by lasers, in the flat panel display industry (Junke Jiao, 2008)and alumina surface (B.S.Yilbas, 2010). Finite element welding models have been developed and simulated with the development of multi physics software's are focussed to discuss on analysis of temperature, microstructure and stress strain field was developed in order to predict and control mechanical properties of weld joint of structural steel and the effect of heat input and inter pass temperature at multipass weld joint of beam to column connections on the strength and fracture (Masao Toyoda, 2004), the absorption variation during pulsed laser welding of electronic Au/Ni coated cu-lead frames (F.H.Kalpan, 2005), an analytical thermal model for weldability of magnesium alloys (Kamel Abderrazak, 2008), Molten pool formation during an interaction of a pulse (Nd: YAG) with a magnesium alloy (Kamel Abderrazak W. K., 2009), the effect of thermal cycling assisted void nucleation of Aluminium alloy (Cheng Jin, 2009), deformation in fillet-welded joint of ship building steels (Dean Deng, 2007), transformation plasticity in steels (J.B.Leblond, 1989),TIG and SAW welded thick steel sheets toward ITER TF coil case (B.Carmignani, 2001), the effects of turbulence on the transport characteristics associated with typical laser welding process of Cu-Ni dissimilar couples (Nilanjan Chakraborty, 2007),the hardened zone in laser treatment of carbon steel (Adam Bokota, 1996), distortions in chassis components of BMW series (C.Hackmair, 2003)and defects are to be expected during fusion welding such as formation of a centre line grain boundary, constitutional liquation at second phases and solidification cracking of super alloy (IN718) (D.Dye, 2001). Also, Simple calculations are given for a variety of engineering alloys, including steels, Al, Ti, and Ni based super alloys (Z.Guo, 2009).

The model-predicted plume front and shock wave front propagation and the compressive residual stress of layer thickness agree reasonably for femto second-Laser shock peening (Benxin Wu, 2010), spot weld strength and the strength can be estimated from the radiation feature using an artificial neural network (Dae-Cheol Lim, 1999), heat flux distribution model of GMA was developed to analyse the spatial distribution of heat flux falling on the weld pool surface has a marked effect on the weld pool shape and on the subsequent solidification process, which in turn affects the structure and properties of the weldment produced (C.S.Wu, 1998), different types of lap joints used in the automotive industry were studied under tension, Three-point and Four point bending by numerical and experimental methods for the automotive industry (S.Z. Shuja, 2008).

The temperature distribution for different thickness of dissimilar plates of low carbon steel and AISI 304 stainless steels are calculated experimentally formultipass welding and hints to establish the microstructural changes, phase transformation and degradation studies from results of average peak temperatures (S.Murugan, 1998). MMA welding of AISI 304 stainless steel and low carbon steel plates of different thickness 3D numerical model was developed based on control volume method to predict the temperature distribution in the HAZ and in the base plate region of bead on plate welding, a good match between experimental and theoretical prediction was obtained (S.Murugan, 1999). Similarly, three dimensional models for temperature distribution of dissimilar joint of 2 mm thick AISI 316L stainless steel and low carbon steel plates weld using pulsed Nd: YAG laser was predicted analytically and using COMSOL code (K.SureshKumar, 2016).

IV. Keyhole Models on Laser Welded Materials

Many numbers of analytical and numerical models of welding process have been developed to evaluate temperature and residual stress and distortion distributions during the welding process of structural components. These include analytical models, two and three dimensional finite element models. However, most of the investigations are limited to local problems of heat source - material interaction (G.A. Moraitis, 2008). It has studied that the very strong density of power delivered by laser beam causes the metal to boil in a few milliseconds of irradiation (Bruno Martin, 2001). The schematic of the pressure created by the intense vaporization tends to dig the molten metal zone as shown in Fig. (G.A.Moraitis, 2009). Then the beam penetrates deeper and deeper in to the matter and the supplied zone becomes a thin hole named key hole. This phenomenon allows deep penetration and high welding speed owing the precise power source and high welding speed, the heat input to the work piece is small and distortions are minimal. Also the shape of the laser weld is less critical for distortions, especially angular ones than the traditional welds. Thus, keyhole formation is the core of laser penetration welding.

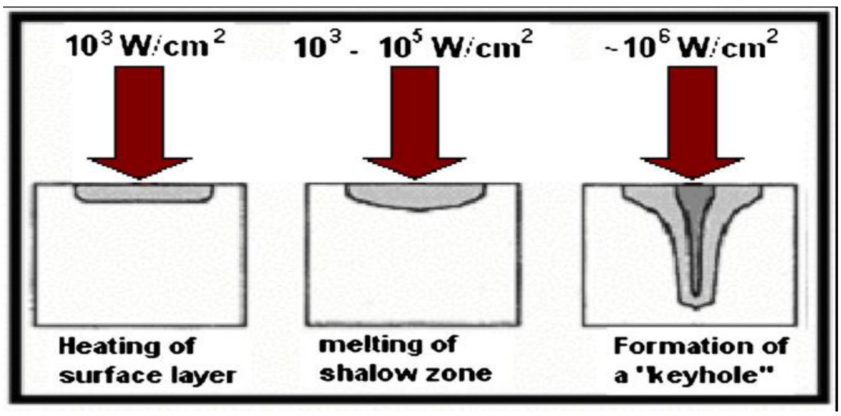


Fig. 4 The formation of a keyhole during the welding process

When a laser beam with high intensity irradiates the work piece, a key hole is formed in the work piece which enables the laser beam in to penetrate deeply in to the work piece (Xiang Zhang Jin, 2003). While in conductive laser welding, the laser energy is absorbed on the surface of the work piece.Schematic of laser beam and work piece interaction and keyhole pattern are shown in Fig. (JohnMichaelDowden, 2001).

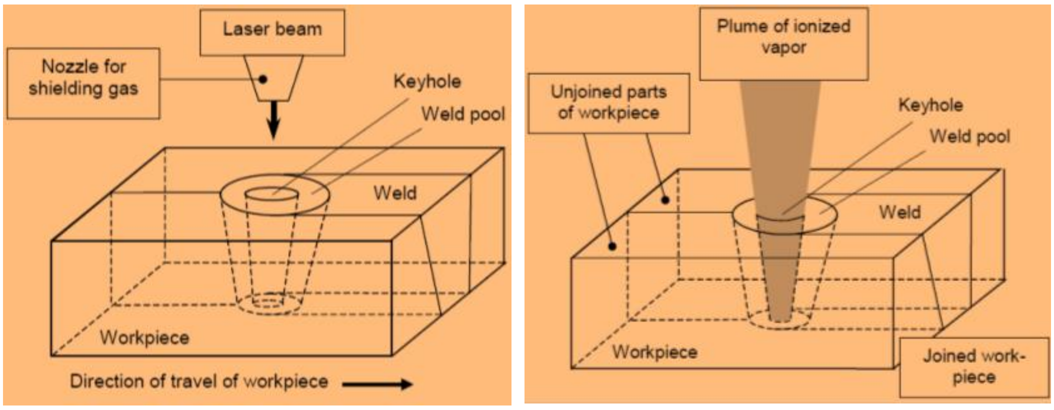


Fig. 5 Schematic of the solid, liquid, and vapour regions in laser keyhole welding

A semi empirical thermal model of predict the thermal field in deep penetration laser welding of thick stainless steel was proposed based on moving heat source theory (B.Binda, 2004). The original solution proposed by Rosenthal had been expanded in order to take in to account the non-homogenous heating along the work piece thickness without considering variation in thermal properties with temperature and phase changes. According to the simulated results (a) the temperature distribution around the impact point has a parabolic form due to Gaussian energy profile. (b) The marangoni flow and buoyancy forces enhance the heat transfer in the molten pool by driving the molten liquid flow (Michael Davis, 1985). The Jaeger – Rosenthal asymptotic particular solution for the quasi steady state problem of moving heat source is proven to be inconsistent with source constant intensity. The problem is reduced to an equivalent Poisson's equation by exponential transformation of moving coordinate scale. Green function was used to represent the general case of surface power intensity distribution in a semi-infinite solid (Levin, 2008). The Davis-Noller solution tries to extend the line source idea to cover the case of a circular isothermal keyhole of nonzero radius. The material elements all move in a straight line, and all those within a distance equal to the radius of the keyhole cross the boiling isotherm into the keyhole (JohnMichaelDowden, 2001). The solution of phase change problems involving moving heat source (C.Prakash, 1987)and temperature profile of a high-quality laser beam (TEM_{00}) induced on moving thin metal foils was calculated mathematically and theoretically (R.Brockmann, 2003).

The characteristics of Lauguerre-Gaussian beams in the non-linear medium are explored and the electric field distribution in the far after passing through the non-linear medium was calculated (Rui-Pin Chen, 2010). The implications for pseudo continuous CO and Nd: YAG laser of a mechanism based on the instability and inherent in variable absorption capabilities of the work piece was investigated. The energy absorbed from the laser beam is perturbed by instability and the fluctuating interference pattern. For the CO laser, this results in a weld that is very similar but slightly superior to CO_2 laser. Nd: YAG laser has a poor mode structure but greater penetration is possible as the length-scale of the fluctuations in the interference patterns is small, compared to the radius of the keyhole until a much greater depth as shown in **Error! Reference source not found.** (John Dowdon, 1996).

It is possible to analyse the pressure at the keyhole wall in a number of different ways. Some approaches suggest that, the pressure in the keyhole may differ substantially from the ambient pressure and the pressure in the liquid state material. Solving heat conduction equation with latent heat was taken in to account is often referred to as the Stefan problem. In the theory of laser welding a solution was arrived for Stefan problem by the method of lines. An explicit finite-difference numerical method was used to calculate the non-steady state 2D (Michael Davis, 1985) and 3D Stefan problems. Simulation was executed by grid code PHOENICS on a fixed grid and concluded that does not require the implementation of the Stefan condition at the solid-liquid interface and verified on TIG and GTA welds (C.Prakash, 1987). More recently, closed form analytical solution for this kind of 3D heat sources in a semi-infinite body or in a thick plate. This enabled them to predict the melt pool geometry.Transient three-dimensional temperature distribution in a 316L stainless steel irradiated by a moving Gaussian laser beam was investigated numerically by means of COMSOL Multi physics 4.2. Convection and radiation from the work-piece surfaces as well as variable thermo physical properties are accounted for the simulation of the investigation on heat and mass transportation across the weld joints of during pulsed laser welding process as shown in Fig. 6 (K Suresh Kumar, 2015).

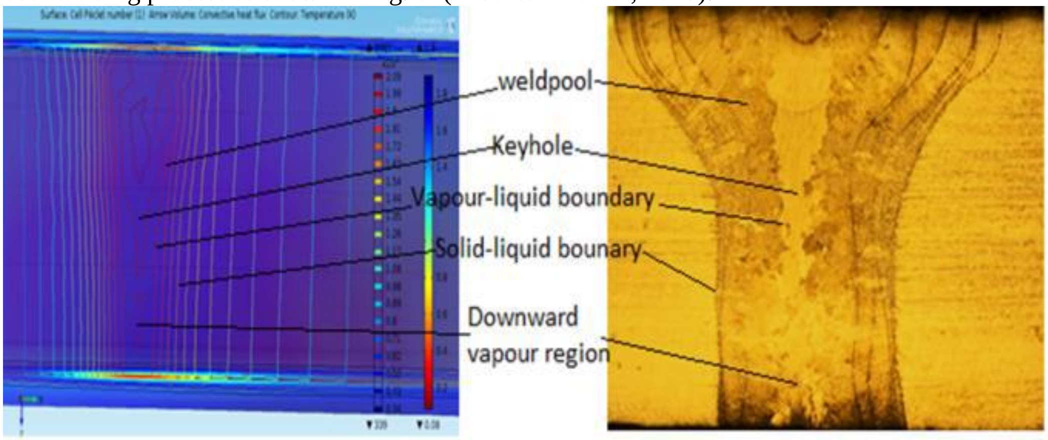
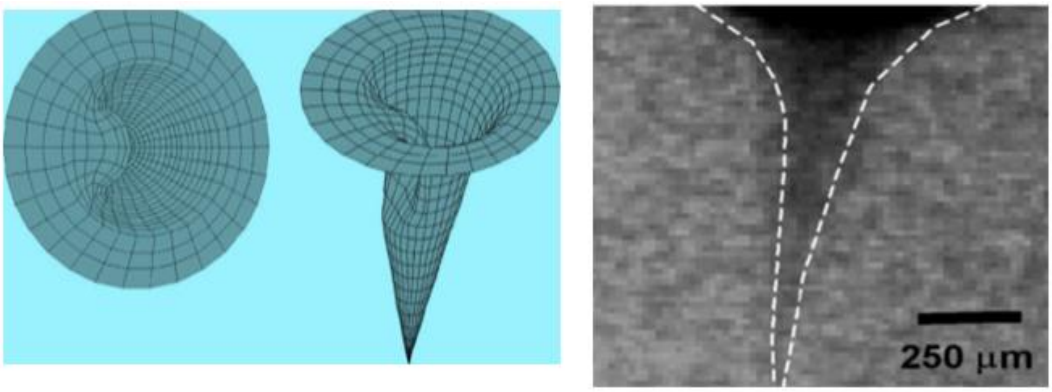


Fig. 6: Comparison on estimated keyhole with an experimental observation of 316L stainless steel joint during pulsed laser welding.

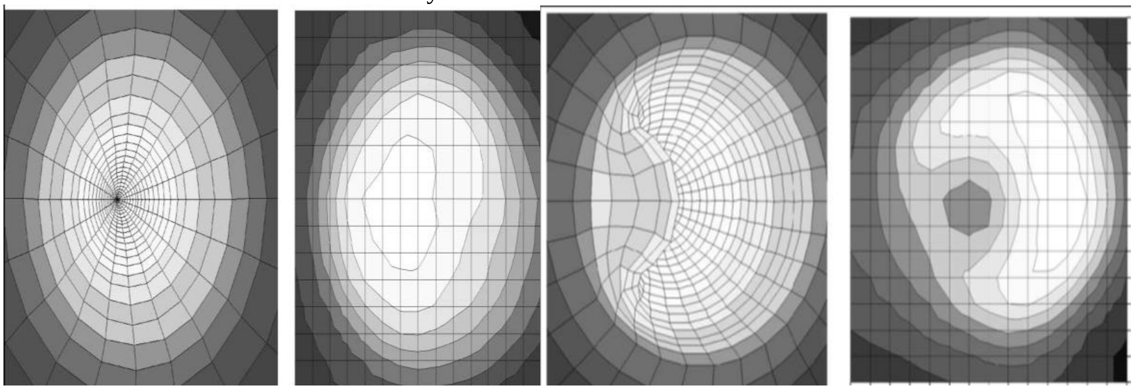
Some electrical effects of keyhole plasma in deep penetration continuous wave CO_2 laser welding using Onsager and De Groot relations were found. Thermodynamic relations applied to keyhole plasma in an attempt to include the effects of thermal and potential gradients. Relations between temperature and the rate of change of electric potential with temperature have been found in the steady case De Groot generalizes Onsager's relations and relates generalized forces linearly to generalized fluxes, obtaining information about the co-efficient in the relation and the ideas can be applied to the keyhole (Phiroze Kapadia, 1996). A boundary element method for three-dimensional steady convection-conduction problem was developed and also a sensitivityboundary element method for the sensitivities of temperature and heat flux along the solid-liquid interface a boundary shape parameter are derived (Junghwan Lim, 1995).A moving heat source model based on Goldak's double-ellipsoid heat flux distribution was adapted to implement heat inputs in to finite element thermal simulation (using a C $^{++}$ programme) of the plate butt joint welding (D.Gery, 2005). The heat source model Gaussian distribution includes complicated phenomena such as, phase transition, heat, mass transferand fluid flow with valid boundary conditions, found good agreement between the model and experiment. This model is useful for predicting heat and mass transfer and fluid flow during continuous deep welding using FLUENT software. A three dimensional transient model for simulating continuous laser keyhole welding process of AISI 304 stainless steel was developed (Renping Wang, 2010).

On the basis of an actual keyhole profile, a conduction model with a cylindrical surface heat was developed for Nd: YAG laser welded stainless steel target keyhole pattern was obtained numerically and experimentally as shown in Fig. (Xiang Zhang Jin, 2003)and (Sung-Hoon Baik, 2001).This model was numerically solved by Finite difference method, temperature field around keyhole and heat flux lost on the keyhole wall was obtained using ANSYS code as shown in Fig. (Xiang Zhang Jin, 2003). When the keyhole is deep enough, it can be treated as a cylinder with Fresnel Absorption Mechanism. After comparison of this pattern with the recorded picture and after adjustment of the keyhole geometry it is possible to see that there exist two classes of welding keyhole a pseudo steady state associated with regular and pseudo constant keyhole shapes, low frequencies of electric current in the plume with good welding results (Bruno Martin, 2001).



(a) (b) (c)

Fig. 7 (a) Structure of keyhole geometry, (b) Virtual view before collapse and (c) Flash radiography of a keyhole in 304L stainless steel.



(a) (b) (c) (d)

Fig. 8 (a) Calculated picture-stable class (b) recorded picture-stable class and (c) calculated picture-unstable class, (d) recorded picture - unstable class.

Welding experiments on mild steel targets was carried out using CO and CO_2 laser beams. The characteristics of the laser beams were nearly some (Spot Diameter and Focus Position) which allows a direct comparison of the welding results of the two laser types. The weld depths obtained with CO_2 laser are reduced using Ar gas, whereas CO laser independent of the assist gas because of lower plasma absorption coefficient for the shorter wave length (M.Schellhorn, 1995). Effect of a transverse magnetic field on the plume emission of the laser-produced plasma of lithium target reveals that the contribution from various atomic processes needs to be considered carefully for modeling in order to find the mechanistic aspect of the change in emission due to the magnetic field (H.C.Joshi, 2010). The modeling of the interaction of laser-sapphire was thermal melting and part of plasma absorption in keyhole; reported that the depth of induced keyhole is approximately directly proportional to laser pulse energy (Jiecai Han, 2009). (M.Van Elsen, 2007) had described that the modelling of heat conduction equation for a localized moving heat source of any type for use in laser material processing such as welding, cladding and alloying. The effects of the temperature dependence of material parameters are investigated, in particular the latent heat of fusion; a finite difference model was implemented, proves the enthalpy method is suited to implement the latent heat of fusion.

A heat source model on comprehensive fluid flow and combinational was developed, simulated and experimentally verified the geometry profile of the weld of laser beam welding of Titanium alloys (Hanbin Du, 2004).Electromagnetic force was used on melt flow of pulsed layer weld AISI 304 stainless steel in order to prevent the porosity by the back filling speed of molten metal during the keyhole collapse process (Jun Zhou, 2007). The keyhole formation with small HAZ distributions around the keyhole was analysed numerically and practically for the different Al, steel and Ti sheet materials joined by an adhesively bonded and laser spot welded lap joint (M.Kermal Apalak, 2003). Effect of heat input causes cracking,heat affected zone in laser welded ATIAllvac 718 plus super alloy and study that shown low heat input welds suffered significant HAZ grain boundary liquation cracking, while no cracking was observed in spite of a more extensive HAZ intergranular liquation in the higher heat input welds (O.A.Idowu, 2007). Low Carbon Steel and Aluminium alloys were welded by keyhole laser mode using lens system (G.Sierraa, 2007). The welding depth had shown the influence on hardness of the weldment. Keyholes weld pool of formation at the butt joint of two different carbon steels (B.N. Upadhya, 2008) is shown in Fig..Further, many more authors have used numerical techniques to evaluate particular problems in heat transfer (D.Gery, 2005).

The line source has proved to be very useful as a simple model of the temperature distribution in keyhole welding. But, it has few of drawbacks, for instance, the temperature predicts is above the vaporizing value sufficiently close to the axis having no accountability. However, it is possible to use it to find an estimate of the keyhole behaviours (Dowden, 2001). The shape parameters of the volumetric heat source, i.e., the radius and depth, are determined from an energy balance equations and experimental fitting, respectively (Jao-Hwa Kuang, 2012). Based on those equations the plasma/vapour zone of keyhole, melt zone and heat affected zone were analytically predicted and simulated using COMSOL code for the butt joint welding of 316L stainless steel-mild steel (refer fig. 9) processed through pulsed Nd: YAG laser (K Suresh Kumar, 2015).

Fig.9: Formation of keyhole in a butt joint of 316L stainless steel- mild steel.

V. Studies on Heat and Mass Transfer During Laser Welding

The thermal history of the laser welding process influences the melt pool behaviour, thermal stresses, microstructure, etc… It helps to predict the final properties of the processed sample such as strength, elongation, fatigue behaviour, hardness and accuracy. Therefore, it is crucial to acquire reliable and accurate predictions of the physical effects that occur during laser welding. The mathematical models are being used to gain insight in the process, as experiments are rather expensive and difficult to test. In general, the source of heat is not concentrated at a point or line but is spread out over the workpiece with an unknown distribution of heat input. In most types of welding, melting and convective heat transfer occurs in addition to conductive heat transfer. In systems like keyhole where convection is the dominant mechanism of heat transfer, the list of dimensionless numbers (ReferTable) are suitable to investigate the way of heat and mass transfer that takes place in and around the entire keyhole. The heat transfer, fluid flow and phase change of the weld pool during pulsed current gas tungsten arc (GTA) welding, including the generalised Navies-stokes equation and electric transport equation was solved by numerical model. The model for pulsed current welding was applied to AISI 304 Stainless steel and compared with the constant current (W.H.Kim, 1998). Peclet number was predicted to investigate about the conductive and convective heat transfer during pulsed laser welding of dissimilar weld joint of 316L stainless steel and mild steel samples for investigation of the heat and mass transportation and flow directions in and around the melt pool keyhole during the process (K SureshKumar, 2015)**.**

Numerical modeling of phase change, fluid flow and heat transfer in material process can be in one, two, (or) three dimensions using a developed toolbox in Maple software (Gustav Amberg, 1999). The ADINAT program can be employed to carryout laser simulations where zones with relative high temperature have to cool rapidly (A.Strauss, 1989). An uncoupled thermal and mechanical analysis was carried out using SYSWELD code in order to model a single bead on plate specimen. The heat source was represented by the Goldak double ellipsoid model available within the code (S.K.Bate, 2009). ALBERTA is an open source tool box and that all our implementations are self-contained and independent of any kind of commercial software. Further ideas to improve the simulated welds are to include the fluid dynamic computations for the melt pool, to include a hot crack prediction sub model (or) to use different material parameters for each of weld pieces (J.Montalvo-Urquizo, 2009). Temperature history and residual stress of vacuum brazed stainless steel plate-fin structure (Wenchun Jiang, 2009) and (Hemanth K.Amarchinta, 2010) stress induced by laser shock peening process of Inconel 716 are simulated by FEA with ABAQUS. Temperature field and the strain distribution was analysed using the non-linear FEM model for preventing welding hot cracking by welding with an intensive trailing cooler (Xitang Tian, 2000).

Temperature distribution of metal by laser beam and arc, generation of metal vapour, absorption of laser beam, current density distribution and plasma flow pattern was numerically modelled and verified (Y.T.Cho, 2011). Temperature and thermal stress field are modelled for laser welded low carbon steel plate (B.S.Yilbas, 2010), tensile residual stress of spot welded of AISI 304 stainless steel (B.W.Cha, 2003), DH36 steel plates (G.A. Moraitis, 2008)Steel and Aluminium (G.A.Moraitis, 2009) and to reduce the possibility of fracture in the process of cutting glass by lasers, in the flat panel display industry (Junke Jiao, 2008), using FEA with ANSYS code (Jamshid Sabbaghzadeh, 2008) and characterised with XRD technique and compared with the predictions, weld zone was examined.

Table 1: Dimensionless numbers that can be used study heat and mass transfer in keyhole.

Dimensionless Numbers	Definition	Remarks
Marangoni number	A measure of the surface-tension-driven convection	To explain the melt with high surface tension pulls more strongly on the surrounding liquid than one with a low surface tension wider, longer and deeper weld pool shapes
Peclet number	A measure of convective heat transfer relative to conductive heat transfer	To explainthe melt flow to the rate of diffusion of the same quantity driven by an appropriate gradient near solid–liquid boundary
Prandtl number	The ratio of the momentum diffusion to heat diffusion; a form of dimensionless velocity	To explain heat transfer during free and forced convection on to the keyhole based on the melt properties
Reynolds number	The ratio of viscous force to internal force; another form of dimensionless velocity	To explain the characterization of laminar or turbulent flow regimes within a similar molten pool that chaotic eddies, vortices and other flow instabilities
Nusselt number	Which is a function of the Reynolds number and the Prandtl number	To explain the convection and conduction of heat flows that are parallel to each other and to the surface normal of the keyhole boundary surface, and are all perpendicular to the mean melt flow in the keyhole
Weber number	The ratio of inertial forces to surface tension forces	The quantity is useful in analyzing thin melt layer flows and the formation of droplets and bubbles in the keyhole

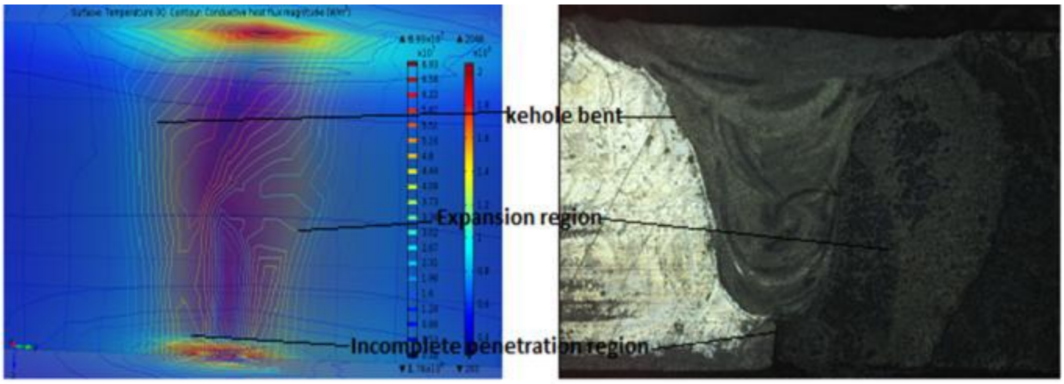


Fig. 11. Contours of heat flow in terms of Paclet number in 316L stainless steel-mild steel joint processed by pulsed laser welding(K Suresh Kumar, 2015).

Few studies on HAZ about the thermal expansion and contraction took place during the laser welding process, which exposes the importance of thermal stress analysis for all kind of welding processes. The influence of thermal stresses and expansion and contraction forces played an important role on the achievement of strong welds (Tensile strength improved 80% as compared to the original thermo plastic substrate) (B.S.Yilbas, 2010).In order to obtain the thermal induced distortions and its influence on the mechanical properties of the welding processes are necessary to consider welding as a thermo dynamical process. In such an approach the thermo dynamical state of material system is characterized by the value of a finite set of state variables.Every aspects of the thermal distribution during laser welding including residual stress has reviewed up to the year 2002 (A.P. Mackwood, 2005). Many bibliographies have been published about boundary element software in engineering (J.Markerle, 1983), finite elements and boundary elements applied in phase change, solidification and melting problem (Mackerle, 1999), the thermal effects due to phase transformation and transformation plasticity (Y.V.L.N.Murthy, 1996), analysis of pressure vessels and piping (Mackerle, 1996), (Mackerle, 2005), simulation of quenching and other heat treatment process and boundary element modelling of surface engineering systems (Mackerle, 2000), FEM and BEM analysis and modelling of temperature distribution and residual stresses (Mackerle, 2001), which are all provides hundreds of references on laser beam welding of 2D, 3D thermo mechanical, linear and non-linear analysis, phase change problems, solidification, melting, austenitic-martensitic phase change, martensitic transformation and solid liquid phase transformation etc… including welding under consideration of austenitic stainless steel and other metals and alloys. Over all, Mackerle has compiled a list of over 800 published papers dealing with FE methods related to general and specific modelling of welding processes.

In industries, welding of modern engineering materials including stainless steel and its alloys find variety of applications due to the need to tailor the location of materials where a transition in mechanical properties, temperature, pressure, and/or performance in service is required. Owing to the wide range of uses with numerous advantages of laser assisted welding process, it is essential to update, understand and model before go it for the industrial implementations.

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