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Prediction of residual stresses in laser welding process using different heat source models

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Abstract

Residual stresses occur due to inelastic deformations, temperature gradients or structural changes and machining process. These residual stresses in welding induced due to contraction, expansion and faster heating cooling of heat affected zone and weld pool. The prediction of residual stresses in laser welding process is planned to carry out using different heat source models. A Python code will be developed to simulate welding process by implementing death and birth technique using different heat source models. Methodology used for achieving the objectives set forth modeling of welding process using modeling software. The models will be then meshed using analysis software. Welding process is simulated under different process parameters. The effects of heat source models on residual stresses are to be studied. The results obtained from numerical and simulation will be validated analytically for different models. The developed code is effectively implemented by integrating with existing system to automate the welding process.

Keywords: Residual stresses, Laser welding, Heat source, Thermal modeling

1. Introduction

Joining materials of similar or dissimilar type in addition to having the desired end material properties after it undergoes various processes is one of the critical parameter to be considered when the material is selected for applications of high criticality. The joining is basically carried out by suitable type of welding, which fuses the materials to be mated by aid of heat.

Welding is an operation thus carried out widely in automotive, aerospace, fabrication and other general engineering industry.

2. Welding Method

In laser welding process a high power density beam and coherent concentrated light is directed at the area of welding interest, appropriate optical lenses are used to focus the light. The beam is absorbed in a thin surface layer and the surface gets fused provided the power density is sufficient enough.

Table 1 : Power density in welding operations

Welding Process	Approx. Power density (W/mm ²)
Oxy-fuel welding	10
Arc welding	50
Resistance welding	1000
Laser beam welding	9000
Electron beam welding	10,000

2.1 Effects of Welding

The welding process leads to rapid heating of the local area which in turn results in high thermal gradients. Thermal stresses are induced in the material as expansion activity of the material due to heating is restrained by the cooler surrounding. Plastic strain is developed in the weld region as the yield limit is lowered in the area of elevated temperature. When the weld area cools down the material in that area will retrieve its strength, normally at an elevated level due to plastic hardening, which in turn gives rise to the residual stresses.

The deformation due to welding is driven by the thermal expansion (temporarily) and the residual stresses (permanently). A high degree of geometrical restraint in welding results in high stresses and small deformations while an unrestrained weld produces lower stresses but larger deformations. Thus residual stress analysis of welding gives us the welding reliability of the design whereas welding deformation analysis helps to assess the feasibility of welding in manufacturing.

Residual stresses are internal forces in equilibrium with themselves over the whole domain of the body. The residual stresses can be distinguished in different levels, first, second and third order residual stresses. First order residual stresses extend over macroscopic area and are averaged stresses over several crystal grains. Second order stress act between crystal and crystal sub regions. Third order residual stress act on the interatomic level. However for engineering purpose the first order stress are of prime interest.

2.2 Simulation of welding for Stress Analysis

Numerical analysis has developed at a fast pace in the past few years due to dynamic development in the computer technology. This advancement is a boon to the welding domain wherein use of this advancement in numerical analysis can help compute complex task in shorter time period. By help of numerical analyses it is nowadays possible to simulate the whole technological welding process and to better understand, on the basis of the acquired results, how the individual input parameters affect the whole technological process, mainly the quality of the resulting material structure and the level of the final contortion and deformation. Series of variables contribute to the end result making welding a highly complex technological process.

The only burden effect during numerical welding simulations is the thermal field distribution at several time instants. Temperature $T(x,y,z,t)$ is an axis function in space and time. The exact thermal field determination during welding (i.e. smelt area form and size in particular) is the first and very important step towards the real determination of the appropriate material structure actual, strains and residual stresses. Thus in relation to the welding simulations it is fundamental to define an accurate mathematical description of the heat source.

For the prediction of a weld bath, so that it matches to real experiments a number of input parameters are needed from many different areas. This is however very demanding both from the economical point of view as well as the determination of a sufficient amount of relevant edge conditions.

When defining the heat source, these numerical simulations do not take into account the flowing in the weld bath, the influence of active elements, type of shield gas, wire diameter, or the changes of mode during metal transmission into the material.

The different heat source models are as below:

- Point source - in the case of deposition on thick section parts surfaces.
- Linear source - in the case of thick section plates welding, where it is possible to disregard the temperature gradient in the direction of their thickness.
- Planar surface - using for flash welding of rods.
- Planar surface with Gaussian distribution mode - comes out from point source and is used mainly for surface hardening simulation.
- Hemispherical surface - also comes out from the point source and is used for arc welding, where it reflects reality better than the Gaussian distribution.
- Ellipsoid source - enhances the hemispherical source where it better reflects reality. It is not used anymore.
- Double-ellipsoid source - in its modified form exhibits the best match with reality for majority of arc

welding methods. Nowadays is used for the majority of commercial simulation programs

- 3D Gaussian - Volumetric source with Gaussian distribution mode

2.3 Gaussian heat source model

3D Gaussian is an example of a heat source model where its conical shape enables to model high energy of the welding process by laser or by an electron beam. From the parametric point of view this model is defined by means of the heat source power, radius of the effected surface and by the throughput depth. Mathematically it is possible to describe the 3D Gaussian by the following equations (1) and (2). The equation (1) describes the heat flow density into material in dependence of spatial coordinate data. The equation (2) supplements the equation (1) by the definition of the radius change in the direction of the throughput depth. Figure 1 shows a schematic view of all the parameters needed to define this model of the heat source.

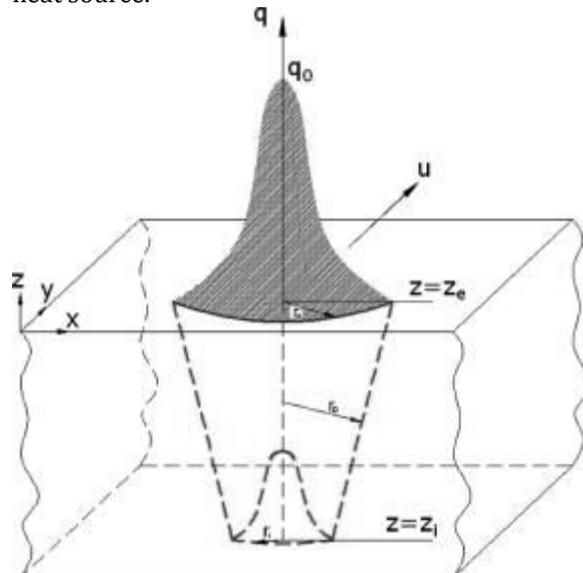


Fig. 1 Gaussian 3D model of the heat source

$$q(x, y, z) = q_0 \exp\left(-\frac{x^2 + y^2}{r_0^2(z)}\right) \quad \dots\dots\dots (1)$$

$$r_0^2(z) = r_e^2 + \frac{r_i^2 - r_e^2}{z_i - z_e} (z - z_e) \quad \dots\dots\dots (2)$$

Where:

- q_0 - heat flow density [W/m³]
- r_e, r_i - determinate 3D Gaussian radiuses [m]
- z_e, z_i - determinate length of 3D Gaussian [m]
- x, y, z - point coordinates [m]

2.4 Formulation of Welding Process

The heat energy equations are referenced in many including Frewin and Scott (1999).

$$k_x \frac{\delta^2 T}{\delta^2 x} + k_y \frac{\delta^2 T}{\delta^2 y} + k_z \frac{\delta^2 T}{\delta^2 z} + Q = \rho c \left[\frac{\delta T}{\delta t} - V \frac{\delta T}{\delta x} \right] \dots (3)$$

For an isotropic conductive material with equal coefficient of conductivity k_x, k_y, k_z (W/mK) in all three chosen orthogonal co-ordinates. Equation (1) gives the heat energy in the weld area with temperature, T (K) obtained both in spatial, x, y, z (m) and temporal, t (s), terms. Q (W/m³ or J/m³s) is the net heat from input and the losses in the form of convection & radiation. Density, ρ , kg/m³, specific heat capacity, c , give the right hand terms of how much heat is retained with respect to time in the material and how much is taken away with the velocity of welding, v , m/s.

The boundary conditions given are $T_0(x, y, z, 0)$ throughout the body at time zero or at the starting of the weld, this is an essential boundary condition. In addition the natural boundary conditions have to be applied consisting of normal conduction k_n , heat flux q , convection $h(T-T_0)$, and the radiation term, $\epsilon \sigma (T^4 - T_0^4)$. Together, the boundary conditions are summed up as: $k_n - q + h(T-T_0) + \epsilon \sigma (T^4 - T_0^4) \dots (4)$

When symmetric boundary and insulation boundaries are considered as adiabatic, with no heat flowing through the surface it is obtained by making convection zero, and conduction zero from the surface. Where, k_n is the thermal conductivity normal to the surface, W/mK, h is the convective heat transfer coefficient, W/m²K, ϵ is emissivity of surface radiating, σ is the Stefan Boltzmann's constant, 5.6710⁻⁸, W/m²K⁴. When it is difficult to use radiation boundary condition, it is combined to convective heat flux by using a modified coefficient, h_r , for hot rolled steel plates with an error of about 5% is,

$$h_r = 2.410^{-3} \epsilon T^{1.61} \dots (5)$$

Radiation inclusion will increase solution time by about three times and hence combined with convection. In laser welding pulsed heat can be given which is available in Ansys to be incorporated. For analytical solution Kronecker δ , is used which takes the value of 1 when pulse is on and a value of 0, when pulse is off thus simulating it as a death and birth form or to say pulsating laser operation.

Finite Element Formulation

The heat equations (3) can be represented in tensor form so the elemental transient heat equation is obtained and later summed to get the system equation which is analysed with time.

$$[K(T)]\{T\} + [C(T)]\{\dot{T}\} + \{V\} = \{Q(T)\}$$

Where K is a temperature dependent conductivity matrix. C is the temperature dependent capacitance matrix based on specific heat it's product with rate of temperature gives heat. V is the velocity vector and Q the heat load on the system. The above equation can be solved numerically, with standard FEM models with Crank Nicholson or Euler time integration models. An initial temperature T_i is assumed, K, C and Q are calculated at that temperature and the next temperature T at $i+1$ is obtained. Again K, C & Q are calculated and temperature at next temperature interval is calculated. The iteration is continued for convergence of temperature or heat flux values.

Assumptions

- Thermal properties, i.e. conductivity, specific heat, density are temperature dependent.
- A combined convection and radiation boundary condition is used on the remaining of the top surface.
- Heat flux of constant used for fusion welding and Gaussian distribution for Laser welding is used on Heat Affected Zone (HAZ).

Finite Element Model

The finite element model of dimensions 40 X150 X 5mm is used. We will be using a conical heat source. The AISI 304 austenitic stainless steel material is considered for simulations to be carried out. The convection is applied on all the surface of the plate except on the heat applied area. The temperature dependent thermal properties for AISI 304 stainless steel material are given in Table 1. These properties were taken from the work carried out Amudala (2012). In the fig.2 shows the meshing of the model with tetrahedral element of volume mesh of 0.02 for whole model.

Table 2: Temperature dependent thermal properties for AISI 304 Austenitic stainless steel

S. No.	Temp (K)	Thermal conductivity, W/m o K	Density, Kg/m3	Specific heat, J/Kg K
1	200	11	8200	350
2	400	15.5	8000	400
3	600	19	7800	440
4	800	22.5	7600	550
5	1000	26	7500	590
6	1200	30	7400	610
7	1400	34.5	7350	640
8	1600	39.5	7300	680
9	1800	44	7200	720
10	2000	47	7200	760

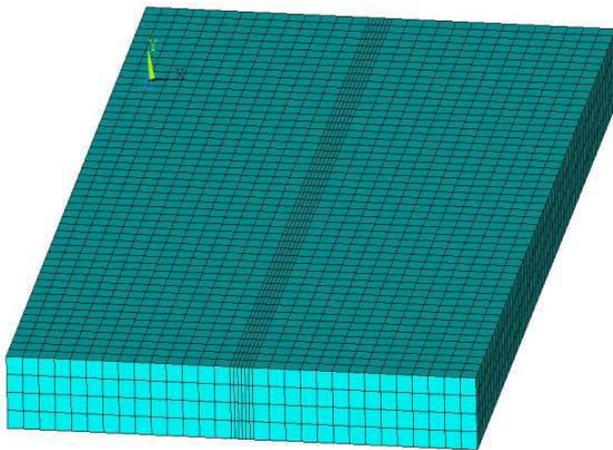


Fig 2: Mesh model used for analysis

Table 3: Properties of AISI 304 Steel

Tensile strength	Yield strength	Density	Melting point	Thermal conductivity	% Elongation
515 Mpa	205 Mpa	8000 kg/m ³	1400-1450°C	16.2 W/m·K at 100°C	20-40

Results:

Thermal analysis - The thermal analysis has been carried out for constant heat flux with welding speed =7.5mm/sec. After the welding phase is finished, the time step is progressively increased up to 1000 sec to allow the plate to cool down to room temperature. In the present work Finite Element Analysis of single-pass butt-welding has been carried out with constant heat flux. For this, a simple Butt-joint welding whose welding parameters are consistent to those of Friedman’s model with heat input Q=1200 W is considered and has been simulated using ANSYS. The temperature will give understanding of weldability in the weldment and also results to effect of structures of due to temperatures in the weldment. In fig.3 shows the temperature distribution in the weldment. The temperature varies from 308 ok to 2374 ok, which results to understand the weldability of the material. The perpendicular of the weld direction is called as the transverse direction. In fig.4 shows the temperature distribution in the transverse direction of the weldment, results shows the maximum temperature is at the fusion zone of the weldment.

The temperatures in the model is various from 308°K to 2374°K. In fig. 5 shows the temperature distribution in the weldment at three zones of the model, i.e. base material, heat effected zone and fusion zone. The fusion zone carries more amount of heat i.e. the temperature is around 2800°K, the heat affected zone is around 1700°K. The simulation is carried for 1000sec the base material was not to cool down to ambient temperature.

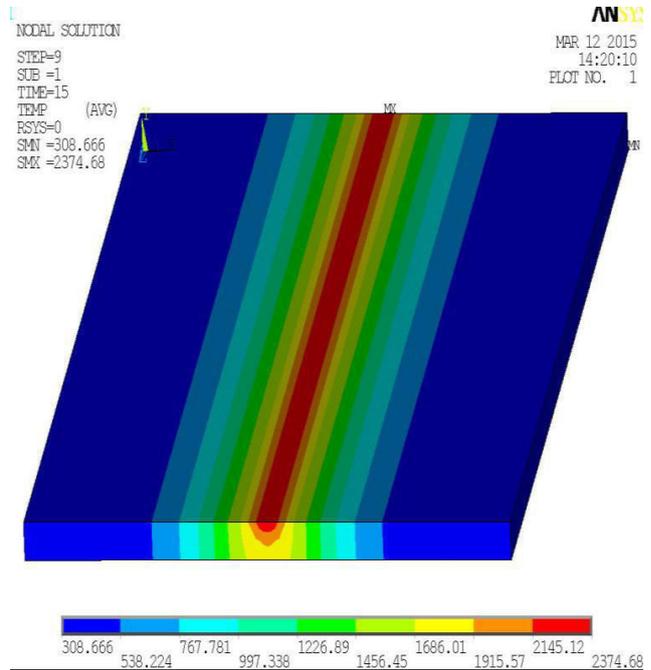


Fig 3: Temperature distribution in the weldment

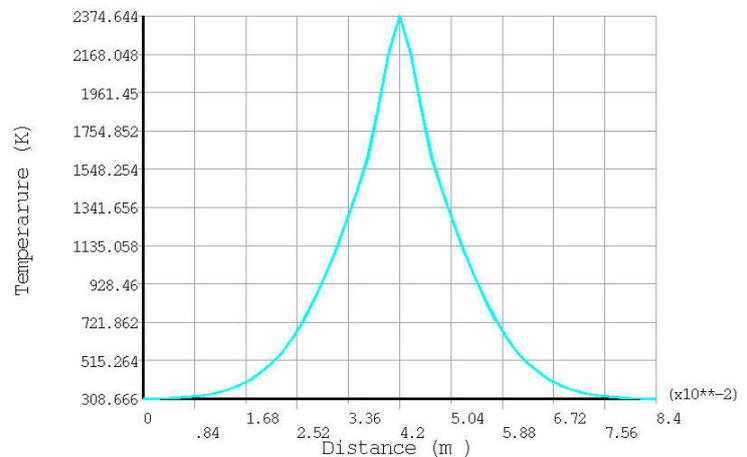


Fig 4: Temperature distribution in the transverse direction of the weldment

Structural results The estimate of residual stresses is analyzed in the weldment. Due to the variance in the temperature gradient, the thermal dependent material properties are given in the model. A stress acting normal to the direction of weld bead is known as a transverse residual stress.

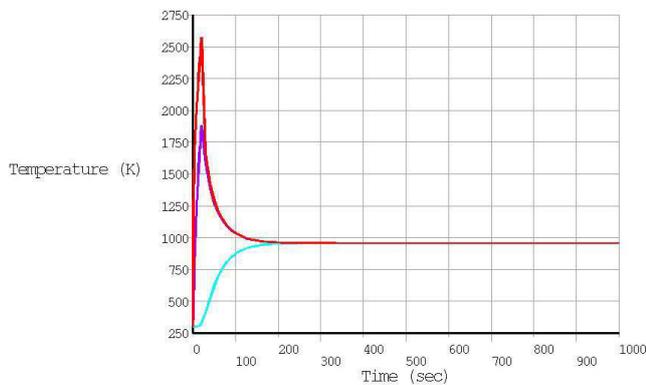


Fig 5: Temperature distribution in the model

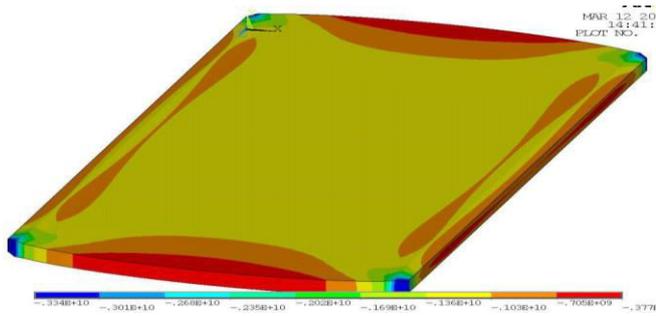


Fig 6: Stress Distribution in the model

The temperature near the weld bead and heat affected zone rapidly changes with distance from the heat source. Residual stress distribution over the plate area of heat input is shown in Fig .6 which shows more stress value in the weld bead area and gradually decreases from center line to the base plate end. Due to the effect of temperature distribution the model i.e. thermal changes which leads to effect in the structural changes; the changes are residual stresses and distortion. In the fig. shows the distortion in the weldment is varied from 0.0378mm to 0.34mm, we can see from the fig. based the thermal distributions the residual stresses and the distribution are varied. The maximum distribution is at the welding joint.

Conclusion

1. A welding process has been simulated using a, ANSYS. First for a constant heat flux and next with a Gaussian distribution more suitable for Laser weld. Using death and birth technique which allows us to simulate in a pulsed manner
2. The temperature near the weld bead and the HAZ decreases rapidly with the distance from the centre of the heat source.
3. The transverse residual is high near the weld and reduces as it moves further.
4. The distortion of the weldment shows low even at the fusion zone.

5. Based on simulation results, residual stress is of the weldment can be predicted. Thus, the experiment analysis, which might be costly, can be avoided.
6. The residual stress for different heat source models can be deduced to analytically find the optimum method to weld the part with minimal residual stress

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