Numerical Modelling and Simulation of a Moving Heat Source during Welding Process

Dr. Ch. Srinivasa Rao.
Professor
Department of Mechanical Engineering
Kallam Haranadhareddy Institute of Technology, Chowdavaram, Guntur, Andhra Pradesh, India

Abstract— Heat conduction of moving heat sources is a topic of interest in engineering problems such as welding, surface hardening, moving friction between mechanical parts, laser treatments etc. There is more impetus on studying a moving heat source both empirically and theoretically. The simulation of a welding process may involve the study on the temperature distribution and cooling rates. The simulation of moving heat source during welding process needs the knowledge of welding parameters, plate geometry and material properties. Study of welding process involves more sciences and variables than those involved in most other industrial processes. A numerical study of transient two dimensional heat conduction problem with a moving source is presented. The main ideas and details of the computational implementation are presented. Numerical results of the simulation of the heat transfer process are reported and validated.

Keywords: heat conduction, moving heat source, numerical modeling

I. INTRODUCTION

Welding is an important topic in engineering research and is widely employed in the fabrication of large structures due to their advantages of improved structure performance, cost savings, and easy implementation.

The problem of transient heat conduction in a plate with a moving heat source captivates attention for many years. There is a great number of theoretical, experimental, and numerical results for this problem starting with the Rosenthal's analytic solution from 1935 [1]. Figure-1 shows the Rosenthal’s moving heat source model and fusion zone length in welding travel direction.

Moving plane heat source analysis have application in several manufacturing processes such as metal cutting, spot welding, laser cutting/surface treatment as well as tribological applications. Analytical and numerical models for the prediction of the thermal fields induced by the stationary or moving heat sources are useful tools for studying the above mentioned problems. Knowing temperature distribution in tribological applications due to frictional heat generation is required to minimize thermal related problems such as lubricant break down. Generated heat at the surface of one body or at the contact interface between two bodies in industrial processes, such as laser welding, breaking systems, friction between two mediums and so on, is often modeled by using the concept of moving heat source in stationary and transient case. Most of this heat is expended on the increase in the temperature of the contact interface. This local temperature increase can strongly affect the surface properties of materials. Thus, the temperature level plays an important role in various applications and should be carefully controlled.

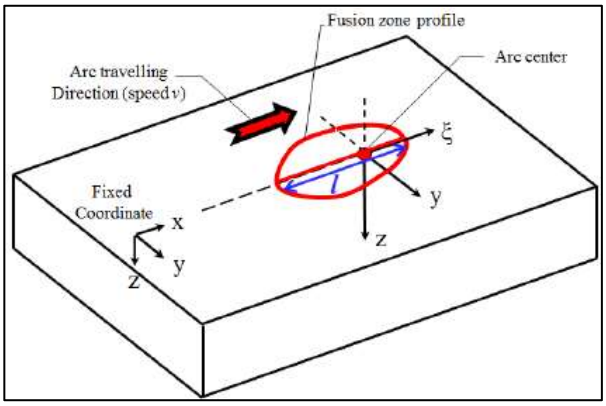

Fig. 1: Rosenthal’s moving heat source model and fusion zone length in welding travel direction [1]

II. LITERATURE REVIEW

A good understanding of the heat transfer process in the moving heat source can be helpful for predicting temperature distribution in workpiece. Until the mid-1930s, the study of the theory of heat transfer from a moving source was neglected, and temperature distribution due to moving heat sources could only be calculated approximately [1]. Daniel Rosenthal published the first literature applying the exact theory of heat flow from a moving source to arc welding [2].

Weld pool shape was approximated by a Gaussian heat source defined by the equation [3]:

$$Q(x,y) = \frac{q}{2\pi\sigma^2} e^{-\left(\frac{x^2+y^2}{2\sigma^2}\right)}$$

where:
Q = heat source, q = net power input and σ = distribution parameter.

The governing equation for three-dimensional transient heat transfer in a solid of semi-infinite dimensions, no heat generation, and no surface losses [4] is:

$$\lambda \frac{\partial^2\theta}{\partial x^2} + \frac{\partial^2\theta}{\partial y^2} + \frac{\partial^2\theta}{\partial z^2} = \rho C \frac{\partial\theta}{\partial t}$$

where:
θ = temperature,
x = direction parallel to weld travel,
y = direction in plane and perpendicular to weld travel,
z = through-thickness direction,
λ = thermal conductivity,
ρ = density,
t = time,
C = specific heat

In the case of a moving heat source applied to a plate that is so thin that temperature does not vary in the through-thickness dimension, the third term becomes zero, and the problem is two-dimensional conduction.

The factors that determine temperature variation through the thickness include welding speed (increases thermal gradient in through thickness direction), thermal diffusivity (decreases thermal gradient in through thickness direction) and thickness (increases thermal gradient in through thickness direction)[5]. A three dimensional non-linear thermo-mechanical finite element (NLTMFE) model was developed for butt welded aluminium alloy 2014-T6 for estimating magnitude of welding residual stresses and their nature of distribution along with thermal history [6]. Finite Element Method (FEM) has been adopted for predicting the bend geometry in laser welding of 1.6mm thick AISI304 stainless steel sheets by considering the effect of latent heat of fusion and the convective and radiative boundary conditions [7]. Analytical solutions for transient temperature field of a semi-infinite body subjected to a moving heat source were found and experimentally validated [8].

Welding distortion is affected by local shrinkage due to rapid heating and cooling and also the root gap and misalignment between parts to be welded. A thermal elastic–plastic finite element method has been employed to estimate inherent deformations for different typical welding joints and used to predict welding distortion for large welded structures [9]. Finite element method is a powerful tool for predicting welding distortion. An interactive substructure method with FEM is developed reduce the computational time in three-dimensional analysis [10]. A theoretical model based on the finite element method has been developed with consideration of the effects of changes in the modulus of elasticity, yield stress and the coefficient of linear thermal expansion of the metal with temperature during welding process [11].Douglas-Gunn alternating direction implicit method has been applied for a transient three-dimensional heat conduction problem with a moving source [12]. A meshless particle method with heat source model based on sticking friction has been developed and is implemented to describe the heat generation of friction stir welding process [13]

A three-dimensional computational weld pool model based on the smoothed particle hydrodynamics method has been developed by taking various forces with shear stress and arc pressure, surface tension, gravity and the welding speed for TIG welding [14]. A computation model has been developed for temperature field in a half-infinite body due to heat source with changeable direction of motion [15]. A mathematical model with an associated numerical technique have been developed to simulate the dynamic impinging process of filler droplets onto the weld pool in spot gas metal arc welding (GMAW) where the filler droplets driven by gravity, electromagnetic force, and plasma arc drag force, carrying mass, momentum, and thermal energy periodically impinge onto the base metal, leading to a liquid weld puddle [16].

Numerical investigation has been carried on arc plasma and weld pool in double electrodes tungsten inert gas welding for analyzing the distributions of current density, heat flux and shear stress at the anode for various electrode separations [17]. It has been found that with an increase in electrode separation the extension of the weld pool alters from the direction vertical to the line through the two electrodes to that parallel to the line. A moving heat source model based on Goldak's double-ellipsoid heat flux distribution and a computer code in C++ language has been developed in order to implement heat inputs into finite element thermal simulation of the plate butt joint welding [18]. A time-dependent welding heat source model has been established for characterization of pulsed current gas tungsten arc welding (PCGTAW). The model was validated by conducting experiments with pulsed current gas tungsten arc deposits on a plate [19]. A three-dimensional finite element analysis is performed for AISI 304 stainless steel thin cylindrical components and the aspects of weld process double ellipsoidal moving heat source geometric parameters are investigated[20]

III. MODELLING & SIMULATION

The moving heat source simulation is carried using a general purpose and commercial software ANSYS Multi physics. The material selected for the simulation of moving heat source is Aluminium with a density of 2707kg/m$^{3.}$ The thermal conductivity of the material is 204 W/mK and specific heat is 896 J/kgK. A two dimensional rectangular work piece 50 x 20 mm 300 x 75 x 10 mm with the heat source moving horizontally along the bottom edge is assumed. The mesh of the 2D model is shown in figure-2.

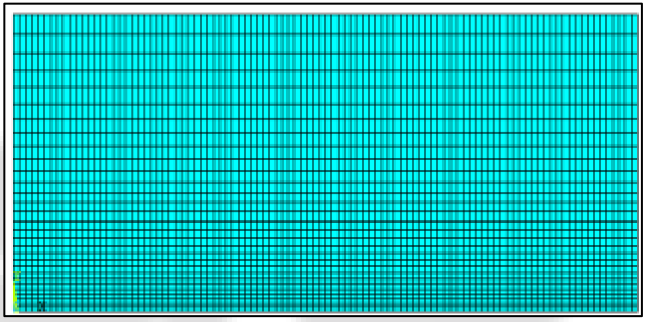

Fig. 2: Two dimensional plate with descretized model.

The heat source is moving from one node to another node in a time variation of 10 sec. Transient thermal analysis has been carried to simulate the moving heat source of 250J. The resulting thermal flux variation that shows the movement of the heat source from one location to another with temperature distribution is simulated and resulting contours are obtained as results. Simulations were performed for a time variation from 10 sec to 60 sec. stepped loading with 5 number of sub steps has been implemented.

IV. RESULTS & DISCUSSIONS

The moving heat source model was made and simulated for transient thermal analysis with in a time period of 10 sec to 60 sec. The figure-3a-figure-3f shows the view of simulation at different positions for thermal flux distribution and clarifies the movement of the heat source from one location to another at various time periods. It was very clear that the heat source has moved from initial location to another location which shows the clear view of heat source movement within a time period of 60 sec. The corresponding nodal temperature distribution at various time periods is also shown in the figure-4a-figure-4d. The vector mode representation of nodal temperature distribution at 60 sec is shown in figure-4e.

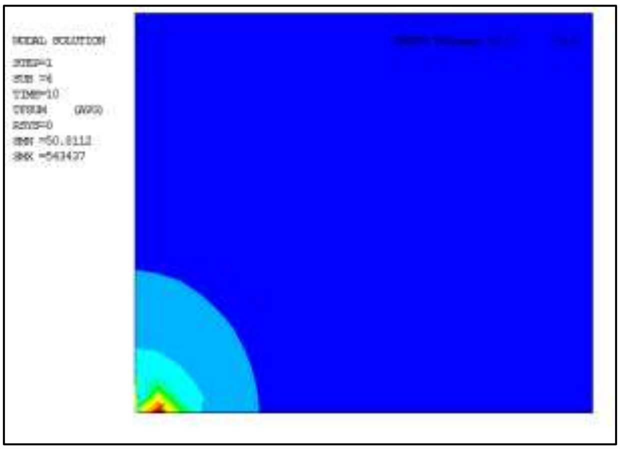

Fig. 3a: Thermal flux distribution at 10 sec

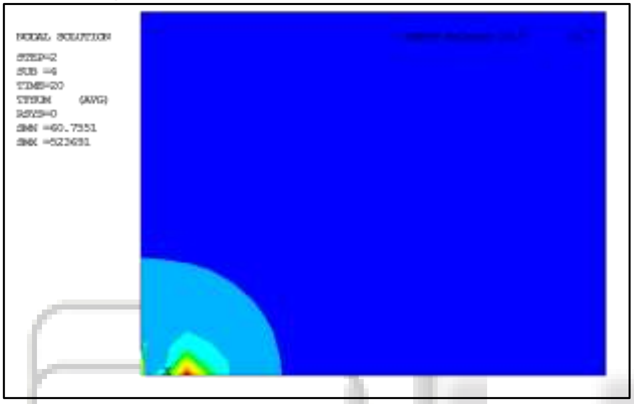

Fig. 3b: Thermal flux distribution at 20 sec

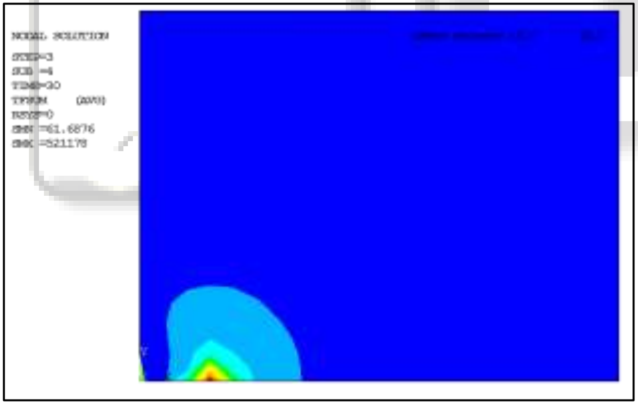

Fig. 3c: Thermal flux distribution at 30 sec

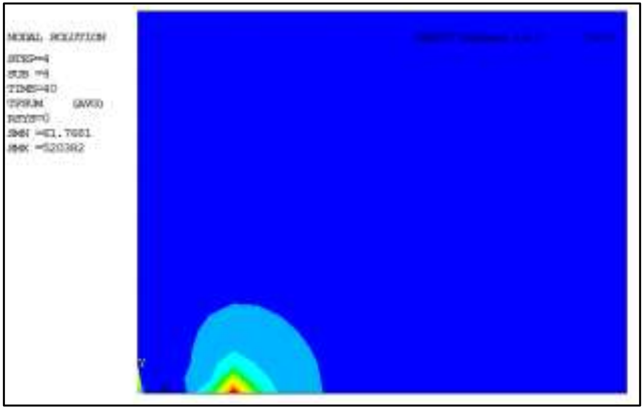

Fig. 3d: Thermal flux distribution at 40 sec

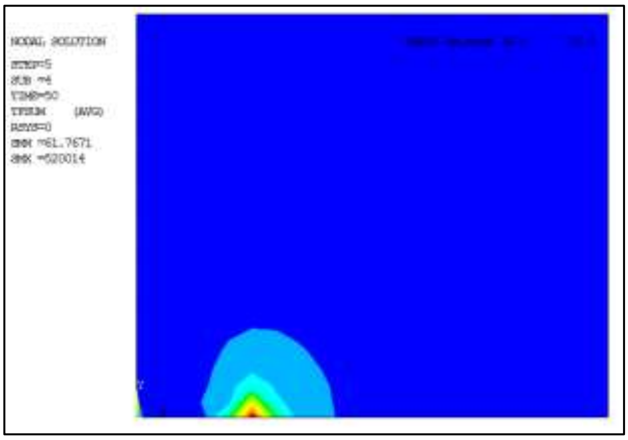

Fig. 3e: Thermal flux distribution at 50 sec

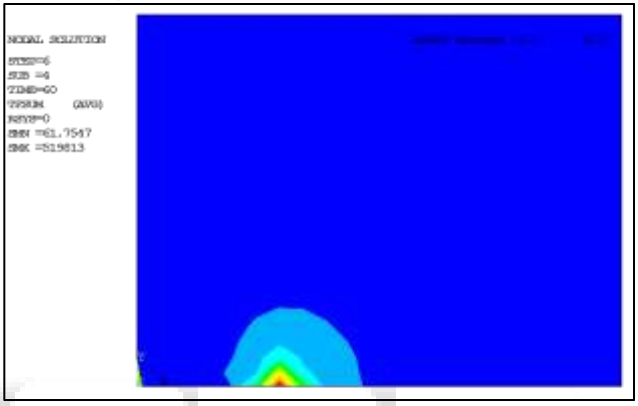

Fig. 3f: Thermal flux distribution at 60 sec

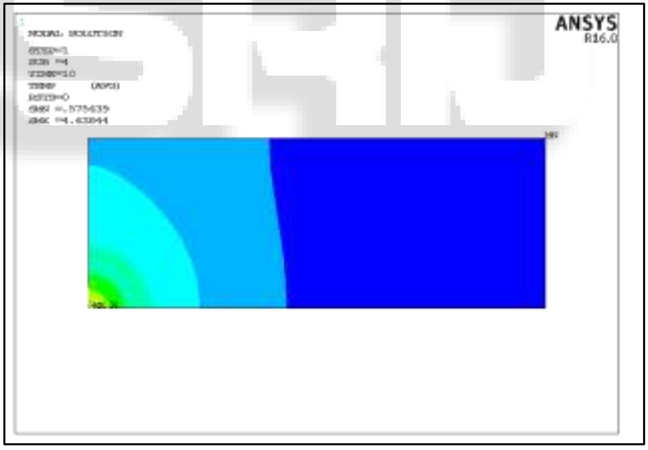

Fig. 4a: Nodal solution for temperature distribution at 10 sec

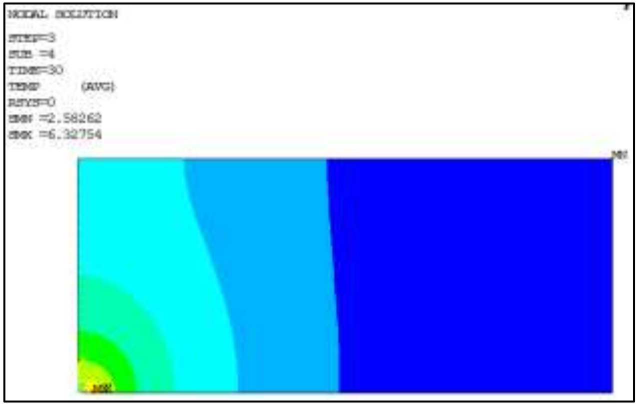

Fig. 4b: Nodal solution for temperature distribution at 30 sec

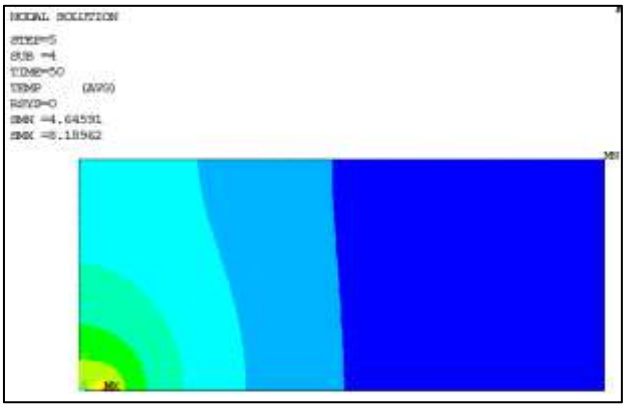

Fig. 4c: Nodal solution for temperature distribution at 50 sec

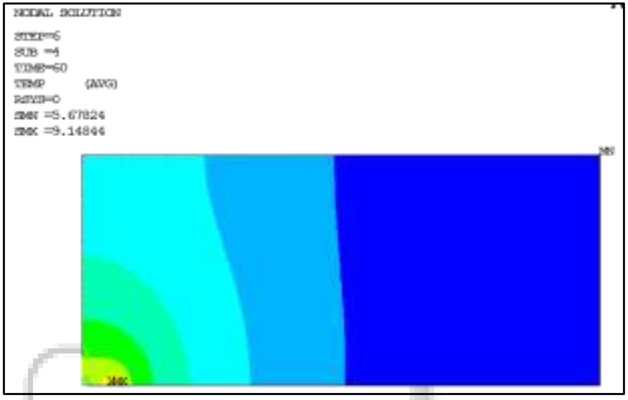

Fig. 4d: Nodal solution for temperature distribution at 60 sec

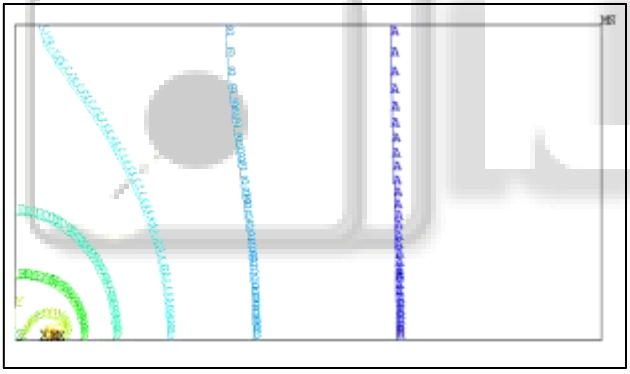

Fig. 4e: Vector mode representation of nodal temperature distribution at 60 sec

V. CONCLUSION

The prominence of moving heat source simulation in various engineering problems has thrusted in taking up the present work and the simulation has been carried successfully. The present paper described a numerical heat source model for simulation of moving heat source. Transient thermal analysis of two dimensional plate has been carried for moving heat source simulation in a time period of 60 sec. The results clearly depicts the movement of the heat source from one location to another within the given time period. The simulation will be the basic plat form for further detailed study of thermal stresses, metallurgical aspects and deformation with convection effects in friction stir welding, surface hardening and mechanisms that involves friction with heat generation and moving parts.

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