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A simplified elliptic paraboloid heat source model for autogenous GTAW process

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ABSTRACT

The applicability of a welding process depends on the rate of heat input, which determines the residual stresses, the heat affected zone and the microstructural changes in the base material. An adequate approach of heat input through a heat source represents a crucial step in the welding thermal field simulation affecting the accuracy of mechanical and microstructural studies. This research work proposes a volumetric-moving heat source for the Gas Tungsten Arc Welding process (GTAW) based on an elliptic paraboloid geometry capable of representing shallow and deep, wide and narrow fusion zones, considering as shape parameters of the heat source, the fusion width and depth penetration. The interaction of the melting material flow in the weldpool and the heat transfer process were analyzed taking into account the effect of convective heat transfer in the heat input distribution in the fusion zone, and the weldpool shape variations during its displacement. The mathematical model for the GTAW thermal field was solved numerically by means of Finite Volume Method (FVM). The elliptic paraboloid model provided a comparable heat input to the classic double ellipsoid model. The estimated temperatures and the predicted geometry of cross-section weld bead by the proposed model are in a good agreement with experimental results.

1. Introduction

Welding is one of the most important joining processes used in automotive, shipbuilding, construction, energetic, aerospace and other industries [1]. It has many competitive advantages over other joining methods, such as enhanced joint strength, low initial cost, reduced preparation time, and a wide range of applications. The GTAW process has successfully been used in the joining of stainless steels, aluminum, magnesium and nickel alloys [2,3]. However, microstructural defects associated with grain growth, phase changes, distortion and residual stresses produced by the thermal cycle induced by the GTAW process affects the integrity of the weld and material properties [4,5].

The above mentioned has prompted a number of research works based on experimental techniques [6,7], statistical methods [8,9] and computational tools [1,10,11] to control processing parameters in order to mitigate welding defects. The heat source which provides the thermal energy of the GTAW process plays a fundamental role in those investigations, interactions between thermal-microstructural fields and thermal–mechanical fields depend on the temperature history produced by the welding process heat cycle [12].

Goldak et al. [13] proposed a heat source model based on the heat input distribution upon a couple of ellipsoids whose geometry has a relationship with experimental measurements of the melting zone, this model has been widely applied in the literature [14–16] giving accurate results in the welding thermal history prediction for a variety of processes and conditions. Nevertheless, the industrial application and recent investigation of Laser Beam Welding process (LBW) and Plasma Arc Welding process (PAW) have led to new approaches for heat source models with a more accurate distribution of heat input in these processes. Wu et al. [17] proposed a heat source model for the PAW process considering the keyhole effect; they took as a reference the melting zone shape and combined a cylindrical source with the double ellipsoidal source. Bag et al. [18] established an adaptive heat source model which updates the value of geometric parameters of source shape with the movement of the weldpool, this model did not need to know the experimental dimensions of the fusion zone previous to the simulation. Pierkaska et al. [19] proposed a cylindrical-involution-normal model (CIN) for the LBW process, in this model the variation of three geometric parameters allowed the change from a paraboloid geometry to a truncated cone to simulate an accurate keyhole effect. A recent research work was carried out

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Nomenclature

q	paraboloid elliptic volumetric heat source (W/m^3)
q_f	frontal ellipsoid volumetric heat source (W/m^3)
q_r	rear ellipsoid volumetric heat source (W/m^3)
a, b, c_f, c_r	semi axes of double ellipsoidal source (m)
x, y, z	spatial coordinates (m)
a_1, b_1	semi axes of paraboloid elliptic (m)
w, l	geometric parameters of paraboloid source (m)
f_h	adjustment factor
t	time (s)
v	volume (m^3)
k	thermal conductivity (W/m K)
f_f, f_r	heat distribution fractions
g	gravity acceleration (m/s^2)
h	sensible enthalpy (J/kg)
f	liquid fraction
h_1	convention coefficient (W/m K)
e	thickness (m)
U	welding speed (m/s)
Q	arc energy (W)
A	area (m^2)
V	net velocity (m/s)
$\vec{V}$	flow velocity (m/s)
C_P	specific heat (J/kg K)
T	temperature (K)
K_f	Carman–Kozeny coefficient

L_0	length (m)
H	enthalpy (J/kg K)
L	latent heat (J/kg)
P	pressure (Pa)
T_∞	ambient temperature (K)
S_u, S_h, S_f, S_b	source terms
T_P	peak temperature (K)
T_m	melting temperature (K)
T_{ref}	reference temperature (K)
F	convective mass flow (kg/m^2 s)
D	diffusion conductance
Y	normal distance to the weld bead (m)

Greek symbols

τ_a	lag factor (s)
ρ	density (kg/m^3)
Γ	diffusive coefficient (W/m K) (kg/ms)
ϕ	transport property (kg^{-1})
τ	surface tension (N/m)
μ	viscosity (kg/ms)
β	coefficient of thermal expansion (K^{-1})
ε	emissivity
σ_a	Stefan Boltzmann constant (5.68×10^{-8} W/m^2 K^4)
$d\gamma/dT$	temperature coefficient of surface tension (N/m K)

for Yadaiah et al. [20] in which an egg heat source model was proposed for modeling welding heat input; this model was obtained from an ellipsoidal shape and aggregated a constant in order to represent an accurate fusion zone cross-section. These models present two common features in their formulation: the cross-section shape of the fusion zone and a Gaussian distribution of the thermal energy.

Goldak et al. [21] suggested five generations of heat source models. The third generation offers more accurate results than the first and second generations due to the incorporation of a fluid flow model and its interaction with the melting zone, but without considering electromagnetic forces. A surface disk with heat Gaussian distribution as a heat source [22–24] was used in some mathematical models which take into account the coupling between liquid material flow and heat transfer in the simulation of welding thermal field. The difference among these models and classical heat diffusion analysis is the consideration of momentum equations in order to simulate the melting flow in the weldpool, the enthalpy-porosity technique [25] and Volume Fraction Model (VOF) [26,27] to represent the fusion phenomena, solidification and the multiphase welding problem.

He et al. [28], Zhang et al. [29] and Mundra et al. [30] applied the enthalpy-porosity technique to simulate fusion and solidification processes in the weldpool using the Carman–Kozeny constant in a source term for the momentum equations. Chung et al. [31] used the VOF model in order to predict the melting region shape and Cho et al. [26] applied the VOF model to represent the bubble formation which produces porosity in the keyhole region in de LBW process and its collapse. Most of the mathematical models proposed in the research works mentioned above were solved numerically using software based on the finite volume method and applying SIMPLE [32] and SIMPLER [33] schemes for the pres sure–velocity-coupling.

This research work proposes a novel volumetric heat source model for the GTAW process based on an elliptic paraboloid geometry, this model concentrates the arc energy heat input in a circular region on the surface. The elliptic paraboloid model tracked the liquid metal fraction in the computational domain in order to produce the heat input, the heat source model moves with a velocity U in the welding direction relative to a non-inertial reference frame attached to it. This model was included as a submodel for the mathematical model describing the welding thermal field. The GTAW process was carried out on martensitic stainless steel plates AISI CrMo 12-1 where thermal history was experimentally measured and compared against the computationally estimated temperatures.

1.1. Description of heat source model

Existing volumetric heat source models are weldpool geometry based. The double ellipsoid model [13] is adaptive to both welding processes shallow and deep penetration, at the same time it can accurately represent wide and narrow melting zones with a non-uniform heat input related with the weldpool geometry. However, the double ellipsoid model requires experimental measurements of four parameters according to its mathematical formulation (Eq. (1)), these parameters represent semi-axes lengths of two ellipsoids. Two parameters are obtained from the fusion zone penetration and width, the last parameters requires the quantification of the melting zone length, which is too complicated [13].

$$q_f(x,y,z,t) = \frac{6\sqrt{3}f_f Q}{abc_f\pi\sqrt{\pi}}e^{-3\left(\frac{x^2}{a^2}+\frac{y^2}{b^2}+\frac{(z+U(\tau_a-t))^2}{c_f{2}}\right)} \quad (1)$$

$$q_r(x,y,z,t) = \frac{6\sqrt{3}f_r Q}{abc_r\pi\sqrt{\pi}}e^{-3\left(\frac{x^2}{a^2}+\frac{y^2}{b^2}+\frac{(z+U(\tau_a-t))^2}{c_r{2}}\right)} \quad (2)$$

On the other hand, in order to simulate deep penetration welding processes like Laser Beam Welding (LBW) and Electron Beam Welding (EBW) the combination of double ellipsoidal and conical heat source models has been used [44]. The conical heat source has a Gaussian distribution of the power in the radial direction [21–45]. The conical source geometry represents an alternative