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Estimation of heat flux parameters during static gas tungsten arc welding spot under argon shielding

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A multi-physics modelling of a static Gas Tungsten Arc Welding (GTAW) operation has been established in order to estimate the heat flux exchanged between the arc plasma and the work-piece. The heat flux was described with a Gaussian function where two parameters required to be estimated: process efficiency and radial distribution. An inverse heat transfer problem (ihtp) has been developed in the aim to estimate these parameters from experimental data. Levenberg-Marquardt algorithm was used as the regularization method in addition to an iterative process. The experiment consisted in a static spot weld with GTAW process. The weld spot was on for 5 s under Argon shielding gas, 2.4 mm pure tungsten electrode on a SS304L disc. Temperatures were measured with thermocouples and weld pool growth monitored with a high speed camera. The experimental data were used to solve the ihtp what led to values such as 0.7 for process efficiency and average radial distribution of 1.8 mm.

1. Introduction

Gas Tungsten Arc Welding (GTAW) is an assembly process by a localised fusion of two materials with the required energy provided from an electric arc plasma. This welding process produces excellent joint quality especially for critical assemblies such as the one required in aerospace, nuclear, petro-chemical industries. In the three last decades, tremendous amount of work have been published in the aim to understand the basic phenomena occurring in arc welding processes [1,2,3,4,5,6]. The use of finite element software are still useful for predicting temperature field and molten flow in the fusion zone. Recently, several welding simulations were performed by considering all the physics involved in the weld pool [6,7]. All these models require the specification of net thermal input from the arc plasma to the work piece surface. Rosenthal [8] proposed a mathematical model of the moving heat source under the assumptions of quasi-stationary state and concentrated point heating in the 3D analysis. Pavelic et al. [9] suggested a circular disc heat source model with Gaussian distribution of heat flux on the surface of work piece. Goldak et al. [10] further developed a double ellipsoidal power density distribution of heat source model below the welding arc to simulate correctly any kind of welding processes. These heat source models have been also used in welding simulation for predicting sample distortions and residual stresses [11]. In this work, a static Gas Tungsten Arc Welding (GTAW) operation has been investigated both experimentally and numerically. It is well known that the heat flux absorbed by the work-piece from the arc plasma relies strongly upon the different welding conditions (welding intensity, shielding gas mixture, electrode size and composition). The heat flux distribution influences the temperature distribution on and in the molten weld pool and consequently the surface tension of molten metal. Modification of surface tension on weld pool surface results as changes of the molten metal flow in the weld pool. So it is a matter of interest to know correctly the heat flux absorbed by the work-piece in order to predict accurately the flow in the molten pool and the final shape of the fused zone. The heat flux was modelled with a Gaussian function involving two experimental parameters which were process efficiency and radial distribution. Then an inverse problem has been stated in order to estimate these heat flux parameters from experimental data. Such inverse problems have been intensively used in the welding literature for the assessment of heat flux, material properties, liquid/solid interface for instance [12,13,14,15]. The resolution of the inverse problem requires a regularization method as well as experimental data such as thermal histories, weld pool evolution. An iterative procedure coupled to the Levenberg-Marquardt technique [16] has been used to solve the stated inverse problem. It was

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considered that some variables involved in the GTAW numerical simulation such as welding current, voltage, material properties, surface tension of molten metal are known with a reasonable accuracy. The inverse heat transfer problem (ihtp) was firstly investigated numerically in order to validate the robustness of solution by introducing errors in the input data. Afterwards, the ihtp was solved with data measured during a GTAW spot weld operation with a duration of 5 s on a SS304L cylindrical disc sample.

2. Mathematical modeling and simulation

2.1. Assumptions and governing equations

The computational model for the current study is limited to the workpiece, with a specific focus on the weld pool. The multiphysics problem comprises electromagnetism, fluid flow and heat transfer [17]. Fig. 1 shows the different transport phenomena occurring in the welding process. The molten weld pool and the different forces considered for the current study are also represented in Fig. 1.

The major assumptions made for the simplification of the problem are:

1 Static TIG welding (the arc is stationary) is carried out and the 2D-axisymmetric model is assumed. The radial position is defined by *r*.
2 Molten metal flows in the weld pool are considered as laminar and incompressible due to the small size of the weld pool.
3 Buoyancy force is taken into account using the Boussinesq approximation [7] as well as the latent heat of fusion.
4 The surface tension coefficient is both temperature and sulfur content dependent using the Sahoo et al. relationship [18].

$$\frac{\partial\gamma}{\partial T} = -A_\gamma - R_g\Gamma_s \ln(1+Ka_s) - \frac{Ka_s}{1+Ka_s}\frac{\Gamma_s\Delta H_0}{T}$$
$$K(T) = k_1 \exp\left(-\frac{\Delta H_0}{R_g T}\right) \quad (1)$$

where parameters A_γ, R_g, Γ_s, a_s, ΔH_0 and k_1 are defined and given in Table 1.

5 A flat weld pool surface is considered. The assumption of a flat pool surface is reasonable because the deformation of the pool surface is low for welding currents below 200 A [19].

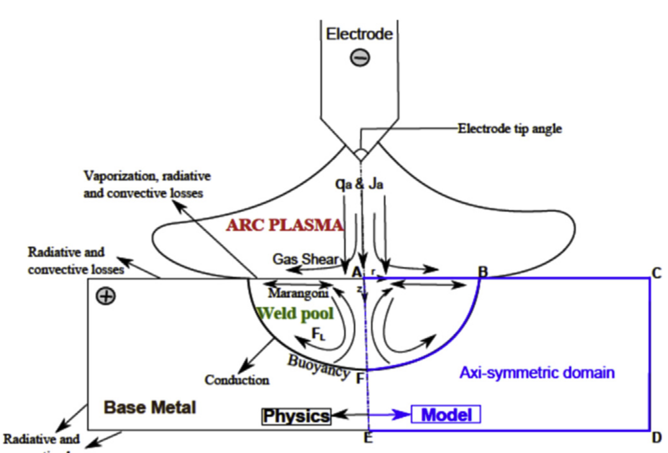

Fig. 1. Schematic of transport phenomena occurring in the GTA Welding process.

Table 1
Material properties of Stainless Steel 304L [20] and welding conditions used in the GTA spot welding simulation. Values for solid state (s) are in the temperature range 293 K - solidus. Values for liquid state (l) are in the range liquidus - 3000 K. Linear dependance with temperature is assumed for the values of the thermophysical properties.

Symbol	Nomenclature	Value
a_s	Activity of sulfur	0.0039 wt%
A_γ	Constant in surface tension gradient	4.3×10^{-4} N m^{-1} K^{-1}
R_g	Gas constant	8314.3 J kg^{-1} mol^{-1} K^{-1}
ΔH_0	Standard heat of adsorption	-1.88×10^8 J kg^{-1} mol^{-1}
Γ_s	Surface excess at saturation	1.3×10^{-8} J kg^{-1} mol^{-1} m^{-2}
k_1	Entropy factor	3.18×10^{-3}
γ_m	Surface tension at pure metal	1.943 N m^{-1}
β	Thermal expansion coefficient	1×10^{-4} K^{-1}
σ_e	Electrical conductivity	$7.7 \times 10^5 \Omega^{-1}$ m^{-1}
L_f	Latent heat of fusion	2.47×10^5 J kg^{-1}
T_s	Solidus temperature	1673 K
T_l	Liquidus temperature	1723 K
T_0	Ambient temperature	293 K
ρ_0	Reference density	7200 kg m^{-3}
$\rho(T)$	Density	s: 7900 – 7200 kg m^{-3} l: 6900 – 5800 kg m^{-3}
$c_p(T)$	Specific heat	s: 480 – 725 J kg K^{-1} l: 800 J kg K^{-1}
$k(T)$	Thermal conductivity	s: 12 – 32.5 W m^{-1} K^{-1} l: 17.5 – 22 W m^{-1} K^{-1}
$\mu(T)$	Viscosity	s: 1×10^5 kg m^{-1} s^{-2} l: 0.0067 kg m^{-1} s^{-2}
h	Convective heat transfer coefficient	15 W m^{-2} K^{-1}
ε	Emissivity coefficient	0.8
I	Current	70 A
U	Voltage	9.4 V
η	Efficiency	0.68
R_B	Gaussian heat distribution radius	1.6×10^{-3} m
CTWD	Contact tip to work distance	2.4×10^{-3} m

6 The spatially distributed heat flux, current and arc drag force falling on the free surface have Gaussian expressions.

The fluid flow in the weld pool is driven by a combination of electromagnetic, buoyancy, surface tension, arc drag and arc pressure forces. The forces involved in the weld pool are depicted in Fig. 1. They can be classified into two categories: the volumetric forces and surface forces. The gravitational force and electromagnetic force which are acting inside the weld pool are considered as volumetric forces. The thermocapillary shear stress (surface tension force) and arc drag force are acting on the boundary of the weld pool and are considered as surface forces. From the previous studies, for low welding currents (less than 200 A), the arc pressure acting normally to the weld pool is negligible and is not taken into account in the present study and that leads to a flat weld pool surface.

The electromagnetic force can be calculated first, independently of the other governing equations as the welding intensity is quasi-constant along the welding operation. Furthermore a steady state analysis is carried out for the electric potential problem as the welding intensity is reached almost instantaneously after striking the electric arc. The computation of Lorentz force requires both terms: current density vector **j** and the self-induced azimuthal magnetic field B_θ. These two terms can be deduced from the solution of electrical potential $\phi(r,z)$ equation, which is given as follows:

$$\nabla^2\phi = \frac{1}{r}\frac{\partial}{\partial r}\left(r\sigma_e\frac{\partial\phi}{\partial r}\right) + \frac{\partial}{\partial z}\left(\sigma_e\frac{\partial\phi}{\partial z}\right) = 0 \quad (2)$$

and the current density is calculated according to Ohms Law