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Analysis of energy flow in gas metal arc welding processes through self-consistent three-dimensional process simulation

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ABSTRACT

A self-consistent three-dimensional gas metal arc welding (GMAW) modeling tool is used to analyze energy flow in an aluminum GMAW process. The mathematical model employed in the tool considers energy, momentum and mass transfer between three interacting domains: the filler wire (anode), the arc plasma, and the workpiece (cathode), which includes the molten pool. The mass, momentum and heat transfer associated with the droplets are also considered. The tool is used to model a bead-on-Al-plate problem and validated by comparing predicted and measured weld profiles. The energy input, transformation, transfer, dissipation due to different physical processes are calculated and analyzed to understand the energy structure and flow in the system for a range of welding currents. The energy efficiency, which is the ratio of the energy consumed in melting the metal to the total energy input into the system, is calculated to study the effect of current input on the system efficiency. The findings from the study provide guidance to engineers in designing GMAW schedules to achieve quality welds with good energy efficiency.

1. Introduction

Gas metal arc welding (GMAW), a low-cost fusion joining process, is widely used in manufacturing industries. The most widely-used approach is direct-current electrode-positive GMAW, where the filler wire is the anode and the workpiece is the cathode. The electrical energy input is consumed by a range of mechanisms; for example, extraction of electrons from the cathode (as described by the work function), transport of electrons through the arc plasma against the electrical resistivity (i.e. Ohmic heating), and emission of radiation from the arc plasma. When the electrons arrive at the filler wire, a large amount of heat is released at its tip, which helps to melt the filler wire and form droplets. Meanwhile, energy is transported from the arc to the workpiece, resulting in melting of the base metal and formation of the molten pool. With the droplets detaching from the wire tip and being merged into the molten pool, the weld is formed. The shape and quality of the final weld are directly related to the distribution of the energy, which in turn is governed by properties of the filler wire, the shielding gas, the base materials and process parameters such as current, voltage, wire feed rate, travel speed, gas flow rate, and distance between the anode and cathode. The effect of the above parameters on the energy flow and hence the weld quality is not thoroughly understood, therefore, engineers usually count on physical trials to develop appropriate parameters to achieve a high quality weld. In such tests, various welding process parameters are adjusted to alter the energy flow so that the resulting weld is sufficient to ensure a strong joint, but is not so large as to cause unacceptable heat distortion or defects in the base metals [1–2]. Thermocouples and thermal imaging methods are commonly used to measure the temperature at points of interest so as to monitor the energy distribution.

Table 1 lists the main physical phenomena to be considered in an electrode-positive GMAW process with respect to its three physical regions: anode (filler wire), arc, and cathode (workpiece), where the electrons flow from the cathode to the anode and the mass of the filler wire is transferred from the anode to the cathode. Each physical region interacts with surrounding regions via thermal conduction, convection and transfer of metal vapor, and loses energy to the surrounding environment via radiation. In addition, filler wire melting and droplet formation occur at the anode, droplet transfer in the arc, and molten pool formation and droplet impingement at the cathode. The flow of electrical current leads to (1) Ohmic heating of the gas, workpiece and filler wire and (2) transfer of energy due to the emission of electrons from the cath-

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Table 1
Physical phenomena occurring in the GMAW process.

Physical regions	Physical phenomena
Anode (filler wire)	(1) Electrical conduction (2) Melting of filler wire (3) Droplet formation and detachment (4) Radiation and evaporation (5) Thermal conduction and convection
Arc	(1) Electrical conduction, gas ionization and electromagnetic field (2) Thermal conduction and convection (3) Radiation (4) Droplet transfer
Cathode (workpiece including molten pool)	(1) Electrical conduction and electromagnetic field (2) Melting in the workpiece and formation of molten pool (3) Impingement of droplets (4) Thermal conduction and convection (5) Radiation and metal evaporation

ode, (3) electrons' condensation at the anode, and (4) the phenomena occurring in the anode and cathode sheath regions. An accurate mathematical representation of the above physical phenomena needs to account for the mass, momentum, energy transfer accompanying each process.

There have been continuing efforts in the welding research community to improve the understanding of the effect of process parameters on the energy flow in order to assist engineers in choosing the optimum welding process parameters. Early work focused on experimental and analytical approaches, such as that of Quigley et al. in 1973 [3]. They analyzed the heat flow in the gas tungsten arc welding (GTAW) process based on experimental measurements and analytic estimations of energy components. Their analysis showed that the potential difference across the anode sheath (called the anode fall in the paper) and the work function were two major sources of anode heating, followed by the Thomson effect and thermal conduction. The convection, evaporation and radiation terms were relatively small. Since the 1980s, with the rapid growth of numerical computation capability, research efforts have been focused on developing computational models that accurately represent the physical phenomena in welding processes, so that the energy terms can be numerically calculated [4–8].

Early modeling work considered static two-dimensional models, where only the cathode region (the workpiece with the molten pool) was modeled, and the arc was represented through boundary conditions using analytical expressions, such as in Oreper and Szekely [9] and Kou and Sun [10]. In later works by Zhu and Tsai et al. [4] and by Fan and Kovacevic [11], the anode and arc regions were included in the models, but still limited to a two-dimensional framework. The two-dimensional models can neither represent the three-dimensional temperature distribution in the arc nor the three-dimensional molten pool profile in the workpiece that occurs when there is relative motion between the cathode and the anode. The first three-dimensional models, such as those presented by Zhang and Cao [12] and Fan et al. [13] for GTAW processes, considered the cathode region only. Subsequently, Xu et al. [5] modeled the anode region (metal droplets), the arc and the cathode region (molten pool) in a three-dimensional model, although limited interactions between the arc and the cathode region (molten pool) were considered. Recently, Murphy [14] developed a three-dimensional GMAW simulation tool that is among the pioneers in modeling the interaction between the arc and the molten pool in a three-dimensional framework. The tool considers the motion of the anode, fluid flow in the molten weld pool, free surface deformation of the weld pool, and the mass, momentum and energy effects of metal droplet transfer.

In this paper, the self-consistent three-dimensional GMAW modeling tool is used to analyze the energy fluxes in the GMAW processes. The mathematical model implemented in the tool is first reviewed. The tool is then used to model a bead-on-Al-plate problem and validated by comparing predicted weld formation to measured weld profiles. The energy input, transformation, transfer and dissipation are calculated and analyzed to understand the energy structure and flow in the welding process for various electrical currents. The energy efficiency, which is the ratio of the energy consumed in forming the molten pool over the total energy in the system, is studied for the different currents. The study intends to provide guidance to engineers in developing GMAW schedules to produce high quality welds.

2. Self-consistent GMAW simulation tool

The self-consistent GMAW simulation tool treats the three main components of the system, the filler wire, the arc plasma and the workpiece with molten pool, in three dimensions, considering each component and the interactions among them. In the simulation, the temperature, electromagnetic field, and current and gas flow fields in the arc plasma and electrodes (the filler wire anode and the workpiece cathode) are first calculated without considering the molten pool. The resulting heat input to the workpiece is calculated, and the formation of the molten pool is then considered, taking into account the effects of mass, heat and momentum transfer from the droplets. The size of droplets are calculated from the wire feed rate and droplet detachment frequency, and the mass, energy and momentum transfers are calculated using a time-averaged approach [15]. The surface profile of the molten pool is determined by minimizing its surface energy, taking into account surface tension and curvature, arc pressure and droplet pressure, and the volume of metal transferred by the droplets, and by applying gravity [14,16,17] as an internal boundary condition. The temperature, electromagnetic field, and current, gas and fluid flow fields in the arc plasma and the electrodes including the molten pool are then recalculated, and the molten pool surface profile is then re-determined. This iteration continues until converged solutions are reached.

Fig. 1 is a schematic representation of the FMAW model computational domain including the anode region (filler wire), the arc region and the cathode region (workpiece). The arc plasma exists between the wire and the workpiece. The anode and cathode sheaths are considered in the model using special treatments, described below. It is assumed that the arc plasma is in local thermodynamic equilibrium (LTE), and that the gas and liquid flow are laminar.

The mass, current, momentum and energy conservation equations are used to govern the fluid flow, and mass, current and energy transfer in the anode, arc plasma and workpiece regions. The detailed mathematical equations can be found in [14]. The mathematical models for the energy transformation and transfer in each region are discussed in the next section.

2.1. Mathematical description of the energy flow in the filler wire, arc and workpiece

In the arc plasma, energy transfer associated with convective flow, Ohmic heating, radiation transfer and droplet transfer have to be considered, in addition to thermal conduction. The gas flow is driven by pressure gradients, gravity, the magnetic pinch force, and momentum transferred from the droplets, and is opposed by viscous drag. The magnetic pinch force is associated with the magnetic field induced by the electric current; the current flow is governed by the current continuity equation, and the magnetic field is