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Numerical Simulation of GMAW Processes Including Effects of Metal Vapour and Sheath Mechanisms at the Electrodes

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Abstract

Gas metal arc welding (GMAW) is a common industrial process used to join a wide variety of materials. In the past numerical models of the GMAW-arc with different complexity were developed. However, recent deficits of GMAW-arc models result mainly due to the axisymmetric formulation of the conservation equations and due to the simplified description of the effects in the sheath layers.

Therefore an additional three-dimensional approach is used, including effects like the motion of the welding torch over the workpiece. Furthermore a new approach for modelling the effects of the sheath layer is presented. Therefore the MHD-arc model is combined with a 2T-sheath model for the non equilibrium layers near the electrodes. For the first step the sheath model is implemented on the cathode sheath layer at the workpiece. The model is used exemplary for a metal-inert-gas welding arc with a ferrous wire.

Introduction

In gas metal arc welding processes (GMAW) the arc is established between the continuously-feed, consumable wire and the workpiece. The properties of the arc and its attachment at the electrode determine the transfer of the liquid material. The arc approach and the arc properties are influenced by the geometries of the electrodes and the temperature and current density distribution in the electrodes. In the past different complex numerical models of the GMAW arc [1-2] and the effects in the near electrode regions [3-5] were developed.

Recent models of the GMAW-arc assume axis-symmetry. In practice, the torch is moved relative to the work piece. Therefore at least the distribution of the temperature in the workpiece is non-symmetric. In this paper a three-dimensional approach are presented including effects of torch movement.

Another important simplification results from the modelling of the sheath region. The effects of the sheath layers are simplified by regarding the heat flux due to the charge carrier. The arc attachment at the electrodes is resulting from the temperature depending electrical conductivity of the plasma in the near-electrode layers (space-charge sheath and pre-sheath). In the presented paper a new approach for modelling the effects of the sheath layer is presented. Therefore the magneto-hydrodynamic-arc model is combined with a 2T-sheath-model for the non equilibrium layer near the electrodes. For the first step the model is only implemented on the cathode sheath layer at the workpiece. In this sheath model the deviation in temperatures of electrons and heavy species, the electron and ion diffusion, the kinetics of the ions and the thermo-field emission of electrons are considered.

1. MHD Arc Model

The simulation software ANSYS CFX is used for the numerical calculations of a three-dimensional non-symmetric steady-state GMAW-process. The computational domain is divided in the welding wire (anode), the shielding gas nozzle, the plasma region and the workpiece (cathode), fig. 1.

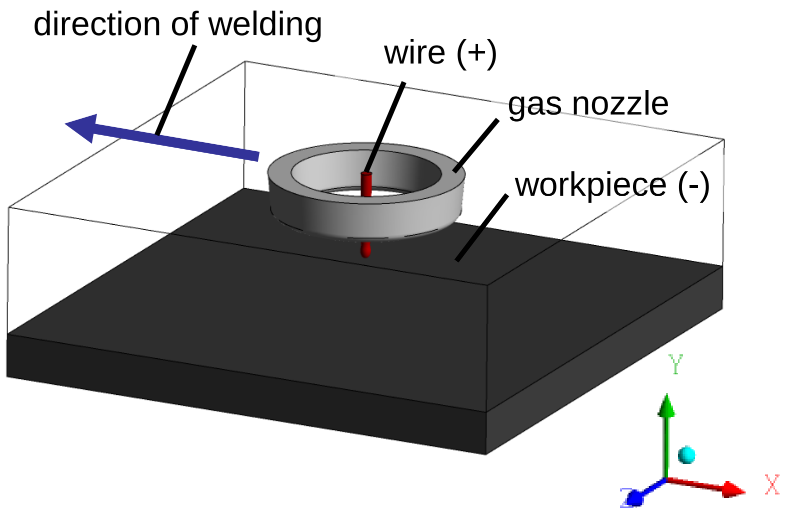

Fig. 1. Computational domain of the MHD arc model

The used equations are based on the magneto-hydrodynamic approximation (MHD). The MHD model combines the equations of the fluid mechanics with the Maxwell's equations of the electro-magnetics [2]. Table 1 shows the used boundary conditions for the equation system.

Tab. 1. Boundary conditions for the MHD arc model

	Boundary	**mass & momentum**	**energy**	**current**	**magnetic potential**	**argon mass fraction**
wire	Top		1800K	250A	zero flux	
	Wire surface		1800K	conservative flux	conservative flux	
nozzle	Top		900K		zero flux	
	Nozzle surface		900K		conservative flux	
plasma	Top	p = 1bar	300K	zero flux	zero flux	in case of Inlet 1
	Front	u_{AD}	300K	zero flux	$0\ T\ m^{-1}$	in case of Inlet 1
	Side	p = 1bar	300K	zero flux	$0\ T\ m^{-1}$	in case of Inlet 1
	Back	p = 1bar	300K	zero flux	$0\ T\ m^{-1}$	in case of Inlet 1
	Shielding gas inlet	V = 18 l/min	300K	zero flux	zero flux	1
	Wire surface	no slip	1800K	conservative flux	conservative flux	-
	Nozzle surface	no slip	900K	zero flux	conservative flux	-
	Workpiece surface	u_{AD}	q_{plasma}	conservative flux	conservative flux	-
workpiece	Workpiece surface		$q_{electrode}$	conservative flux	conservative flux	
	Front		300K	zero flux	$0\ T\ m^{-1}$	
	Side		300K	zero flux	$0\ T\ m^{-1}$	
	Back		300K	zero flux	$0\ T\ m^{-1}$	
	Bottom		zero flux	0V	zero flux	

The arc is assumed to be in local thermodynamic equilibrium. Besides the pressure and temperature dependence, the fraction of the metal vapour inside the plasma is considered. In the presented model the material properties of argon-iron mixtures from the datasets of MURPHY [6] are used. The plasma radiation is treated by the net emission coefficients (NEC) model. The NEC of argon and iron are defined as a function of the temperature. Here, the datasets of MENART [7] are used. For the solid regions, the properties of pure iron material are used.

In a GMAW process the metal vapour is mainly produced by the vaporization of the wire material. In this paper a fixed vaporization mass flux of 1% is assumed, which is referenced on the wire feed. To calculate the distribution of metal vapour and to consider demixing effects in thermal plasmas due to high gradients of concentration, temperature, pressure and electric field strength the formulation from MURPHY [6] is used. An advection source term is used in the energy equation of the workpiece to calculate the temperature distribution in the workpiece due to the motion of the welding torch. The source term and the advection velocity are as follows.

$$S_{SA} = -\mathrm{div}\left(\rho\vec{u}_{AD}c_pT\right). \qquad (1)$$

2. 2T-sheath Model

Determination of the heat balance between the plasma and the electrode requires the description of corresponding near-electrode region. In this region pronounced deviations from the local thermodynamic equilibrium (LTE) are localized. Therefore, the standard LTE models which are used for simulation of arc discharges fail to predict the properties of this layer. An established approach to treat the departure from LTE is the use of a simplified description of the boundary region in form of a system of zero-dimensional conservation equations for particle and energy fluxes [4-5].

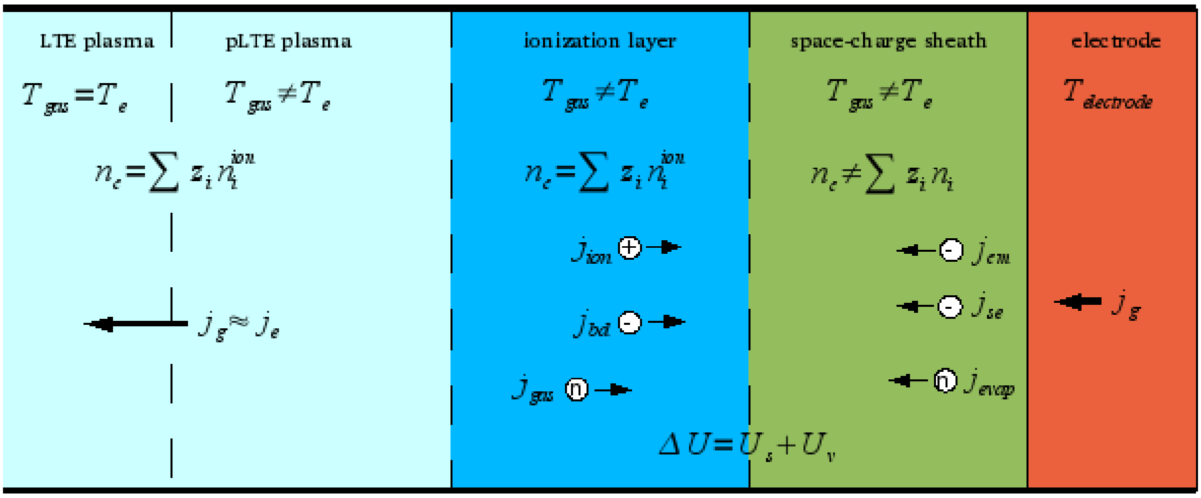

Fig. 2. Qualitative spatial structure of the cathode region of arc discharge

Fig. 2 shows the qualitative spatial structure of the cathode region. Each layer can be associated with a specific feature departing from equilibrium. Thus, in the layer of thermal relaxation (pLTE plasma) the temperature of the electrons T_e begins to decouple from the temperature of the heavy species T_h. In the ionization layer the ionization and chemical equilibrium is distorted due to dominance of ionization processes and diffusion. Finally, in the space-charge sheath the quasi neutrality is violated. The model applied in current investigations is similar to that presented in [5]. It considers the cathode region to be composed of two layers: the space-charge sheath and the ionization layer. The layer of thermal relaxation has been neglected. Deviations from the equilibrium state have been accounted for by consideration of two characteristic temperatures, i.e. the electron temperature T_e and the gas temperature T_h (temperature of ions and neutrals). Both T_e and T_h are assumed to be constant inside the cathode region. The plasma components are the electrons, the ions and the neutrals. The composition of the gas mixture in the boundary region was determined from known particle densities in LTE plasma using the approach described in [5].

The total current density inside the cathode region arises from the fluxes of ions j_{ion}, electrons emitted due to thermionic emission j_{em} and ion bombardment j_{se} , and the flux of high-energy electrons j_{bd} drifting back from LTE plasma toward the cathode. The same fluxes contribute to the energy balance of the cathode region. Additional energy input terms are the Joule heating and the flux of metal atoms, while the additional loss terms are the ionization and the energy used for ion acceleration in the sheath. The net heat flux J_{net} from the sheath toward the cathode results from kinetic energy flux of ions, surface recombination, energy flux of neutral species from LTE plasma, flux of neutral species after the ion recombination at the cathode surface, total electron flux and surface radiation.

3. Coupling of the MHD-arc Model and the 2T-sheath Model

The coupling between the MHD-arc model and the 2T-sheath model is realized by the scheme presented in Figure 3. The MHD model determines the current density $\vec{j}$, the plasma temperature T_h, the surface temperature of the electrode T_c and the particle densities of the plasma for each cell along the interface between the plasma and the electrode. The sheath model calculates the heat flux from the plasma q_{plasma}, the heat flux to the electrode $q_{electrode}$ including the heating effects in the sheath layer and the total voltage fall U_c over the ionization layer and space-charge sheath. Those parameters are further used in the next iteration in the MHD model to calculate the new distribution of the plasma temperature, the temperature of the electrode and the current density.

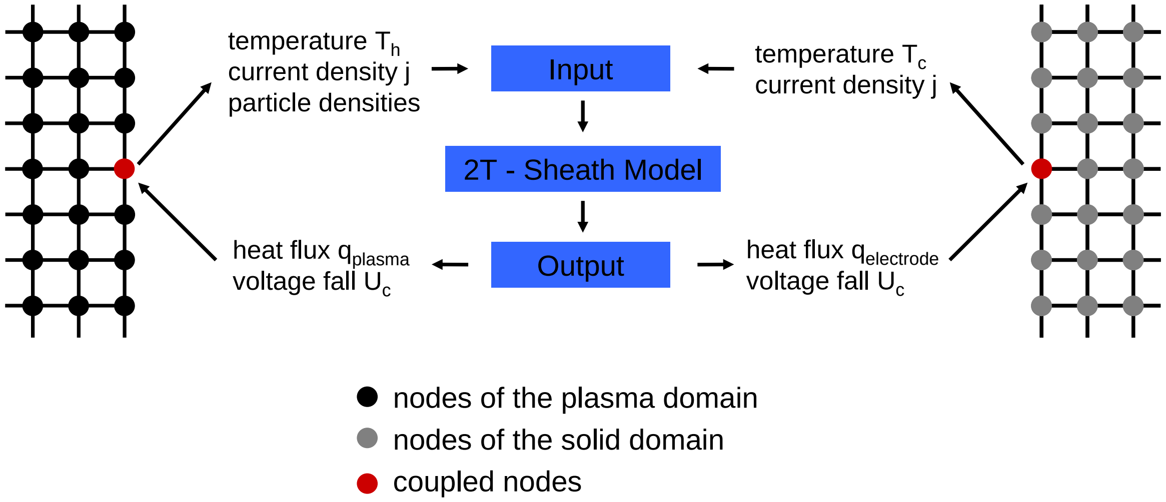

Fig. 3. Coupling between the MHD-arc model and the 2T-sheath model at the fluid-solid interface

4. First Results of the Coupled Models

The presented model of the GMAW-arc is used exemplarily for a metal-inert gas (MIG) welding arc with a ferrous wire. The process parameters used are as follows: $I = 250$ A, $V_{ShieldingGas} = 18$ l/min (pure argon), $d_{Wire} = 1.2$ mm, $u_{Welding} = 0.6$ m/min, $v_{Wire} = 10$ m/min.

In Figure 4 the first results of the MHD-arc model in combination with the 2T-sheath model of the cathode region are shown. It is good to see that the arc tends to form cathode spots which are located at the front side of the weld pool but however not at the hottest region of it. Recent results indicate spots at temperatures between 2300-2800 K. Thus, the predictions are in agreement to former investigations of cathode spots in TIG welding. It seams that the current path is much more influenced due to the sheath than due the pre-sheath effects.

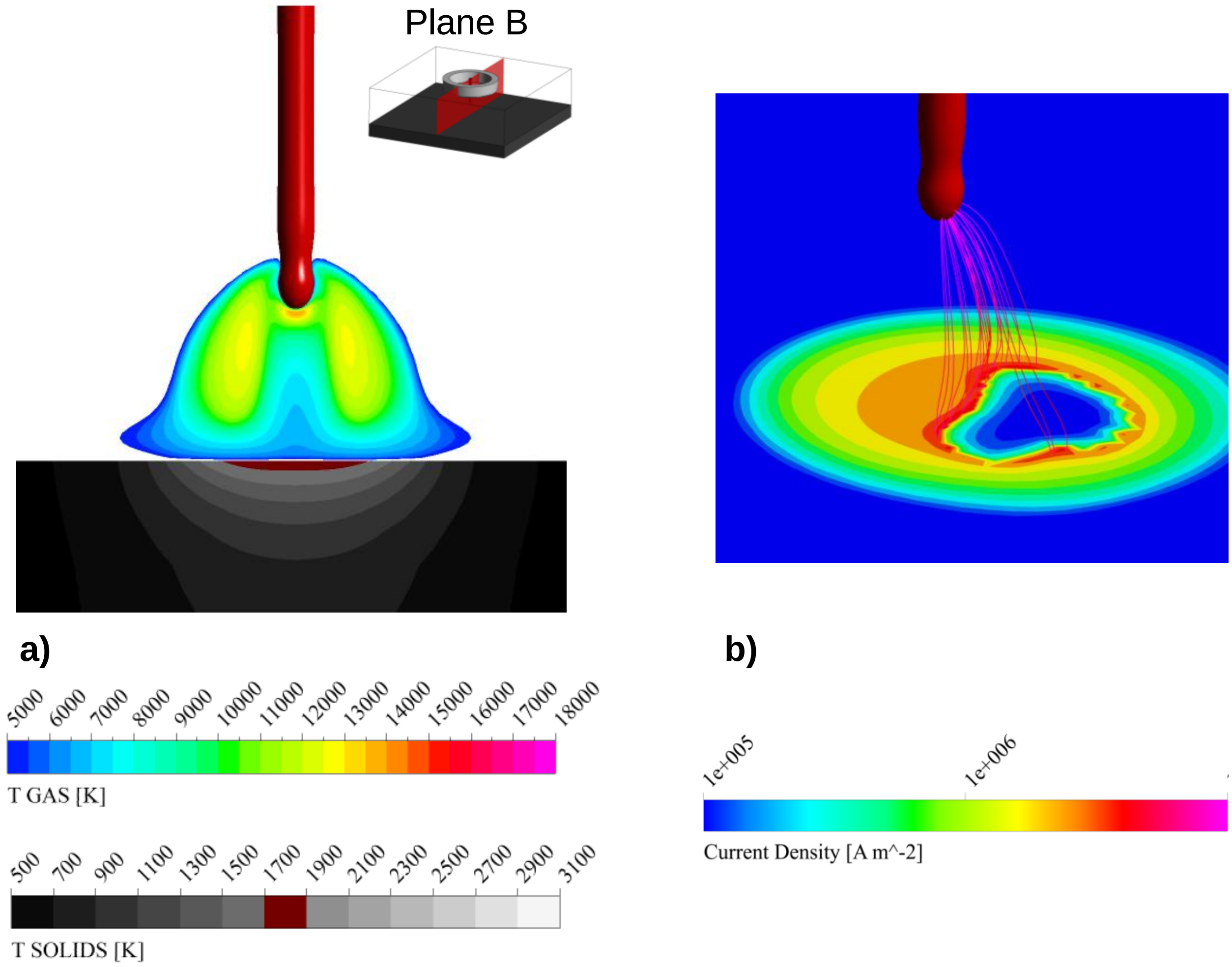

Fig. 4. Calculated temperature distribution of the arc and workpiece in the plane normal to the welding direction (a) and current density distribution on the surface of the workpiece (b) for a 250 A arc with a wire vaporization rate of 1 % relative to a wire feed of 10 m/s for the three-dimensional GMAW-arc model with the 2T-sheath model including the heating effects and the voltage fall in the sheath layer

However a lot of shortcomings of the models remain. They results due to interfacial problems and the very transient behaviour of the spots. Thus the displayed results are only a first report of recent work content.

Conclusions

The paper presents investigation in the arc behavior of GMAW. Therefore a three-dimensional approach is used to consider the torch movement. Furthermore the MHD arc model is coupled with a 2T-sheath model of the cathode in order to improve the prediction of arc attachment at the workpiece.

Due to the three-dimensional model it is possible to investigate the influence of the movement of the torch. In order to improve the model predictions of the arc attachment at the workpiece, it is necessary to consider non-LTE effects in the cathode sheath regions. This paper gives a short report about the current work. The first results demonstrate the forming of several cathode spots that are located at the front of the weld pool.

Acknowledgments

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