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WELDING ARC PLASMA PHYSICS

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I. INTRODUCTION

The problems of weld quality control and weld process dependability continue to be relevant issues in modern metal welding technology. These become especially important for NASA missions which may require the assembly or repair of larger orbiting platforms using automatic welding techniques. To extend present welding technologies for such applications, NASA/MSFC's Materials and Processes Lab is developing physical models of the arc welding process with the goal of providing both a basis for improved design of weld control systems, and a better understanding of how arc welding variables influence final weld properties.

The physics of the plasma arc discharge is reasonably well established in terms of transport processes occurring in the arc column itself, although recourse to sophisticated numerical treatments is normally required to obtain quantitative results. Unfortunately the rigor of these numerical computations often obscures the physics of the underlying model due to its inherent complexity. In contrast, this work has focused on a relatively simple physical model of the arc discharge to describe the gross features observed in welding arcs. Emphasis was placed on deriving analytic expressions for the voltage along the arc axis as a function of known or measurable arc parameters. The model retains the essential physics for a straight polarity, diffusion dominated free burning arc in argon, with major simplifications of collisionless sheaths and simple energy balances at the electrodes.

II. ARC DISCHARGES

An arc discharge is an intense plasma with the addition of significant amounts of neutral gas which serves to replenish the loss of charged particles through electron-neutral ionizing collisions. In a welding arc, this neutral gas is normally a mixture of an inert support gas (argon or helium) and metal vapor from the work-piece. An important approximation often assumed to hold for the arc discharge is that of "local thermodynamic equilibrium" (LTE) between all the charged and neutral particles. This allows considerable simplification in the analysis, since once the electron temperature, T_e, is found, it can then be assumed that $T_{ion} = T_{gas} = T_e$. The discharge can then be modeled as a single temperature fluid, driven primarily by electron dynamics. In a highly ionized arc discharge, electron-ion recombination is enhanced by the presence of the neutral species, producing additional energy losses by radiation. This may be significant for higher current arcs where one should also include "magnetic pressure" effects induced by the arc's self magnetic field. Unfortunately for analytic modeling approaches, these processes can only be treated realistically by numerical solution of nonlinear momentum balance equations in the bulk plasma. In the sheath regions of a high pressure arc, the plasma particles may also experience collisions due to locally high neutral densities. This adds considerable complexity in solving the sheath equations to obtain the sheath electric field.

III. SIMPLE ARC MODEL

Neglecting radiation losses, collisions in the sheaths, the influence of the arc self magnetic field, and assuming that only argon gas is present in the arc column, simplified plasma equations were solved for the cylindrical arc of Figure 1, using a Basic program outlined in Figure 2. The electron temperature was estimated based on balancing diffusive losses and ionization gains in the positive column (PC). Assuming LTE condition, the charged particle densities were determined based on equilibrium energy partitioning using the Saha equation. The ion and electron mobilities were obtained using energy averaged collision cross sections for Coulomb scattering and momentum exchange between electrons, ions, and neutrals. Then a simple current balance in the PC was used to find the electric field and drift velocities of charged particles into the sheaths.

Simple energy balances at the bounding electrodes, along with Poisson's equation, were used to obtain the cathode and anode voltage drops. This gave a Child-Langmuir potential distribution at the anode, assuming only electrons were present in the anode sheath. At the cathode, however, the charge contributions from plasma ions, J_+, plasma electrons, J_-, and surface emitted electrons, J_b, were included in the Poisson integration. These various current densities are depicted in Figure 1. The potential at the cathode was determined in terms of a parameter, $\{J_b/J_{net}\}$. This parameter was set to a nominal value of 0.85, indicating that 85% of the current at the cathode was due to surface electron emission. In general, this ratio should be independently determined based on detailed heat flux balances and known emission mechanisms. The results of this model demonstrated order of magnitude agreement with typical values for V_c, V_a, and the electric field in PC, with good trend fitting when the arc pressure was varied. However, the model failed to demonstrate important features of the arc voltage variation with arc current.

IV. FURTHER CHALLENGES

A. *Basic Model Improvements*: Several improvements in the model can be incorporated by simply relaxing assumption made in the simple model.

1. Add arc self magnetic field effects.
2. Add inelastic collisions (recombination and electron attachment).
3. Add neutral gas flows. (MHD equations to obtain property flow fields.)
4. Include vaporization of the work-piece.

B. *Plasma-Surface-Interactions*: In any model of the arc discharge, a key area of uncertainty lies in how one treats the important interaction between the discharge and the bounding electrodes. For thermionic emitting surfaces, electron emission from the electrode can be modeled by traditional thermionic and/or field assisted emission mechanisms. However, when the welding current is "reversed", the work-piece becomes the dominant electron emitter. In addition to non-thermionic emission mechanisms, the work-piece is being rapidly melted and vaporized. Further complexities arise when this work-piece is oxidized, since the surface oxide structures must first be broken down and removed as the weld proceeds. Recent high speed photography of both reverse TIG and VPPA welding of aluminum suggests that oxide enhanced electron emission from the work-piece may also play a significant role in establishing a "dynamical equilibrium" character for the arc, via charge buildup and subsequent breakdown of the oxide dielectric layer. From this evidence, and the need to extend the plasma arc model for the reverse polarity mode, it is essential that further work extend our knowledge of emission processes.

C. *Experiments to Simplify Model Development*: Essentially all of the basic model improvements listed above involve numerical solution of non-linear partial differential equations. Such an undertaking is probably beyond the scope of interest for near term solutions for weld process development. It would seem prudent to first study the surface emission problem to establish details of the emission mechanisms, and then couple these results with a simpler model such as outlined in this work.

Due to the dynamic character of the emission problem, scoping experiments may be suggested to first illuminate the physical processes involved. In contrast to the plasma arc processes, which are reasonably well established by modern theories, these surface dominated phenomena are presently only speculatively identified. Concerning oxide enhanced electron emission effects, for example, a simple experiment would be observation of differences in arc behavior and weld quality for various configurations of oxide present on the work-piece. Similar experiments could be done using different support gases to differentiate the importance of sputtering effects. It would also be useful to obtain the voltage and current waveforms of the arc during these experiments for correlation with the differences in emission processes.

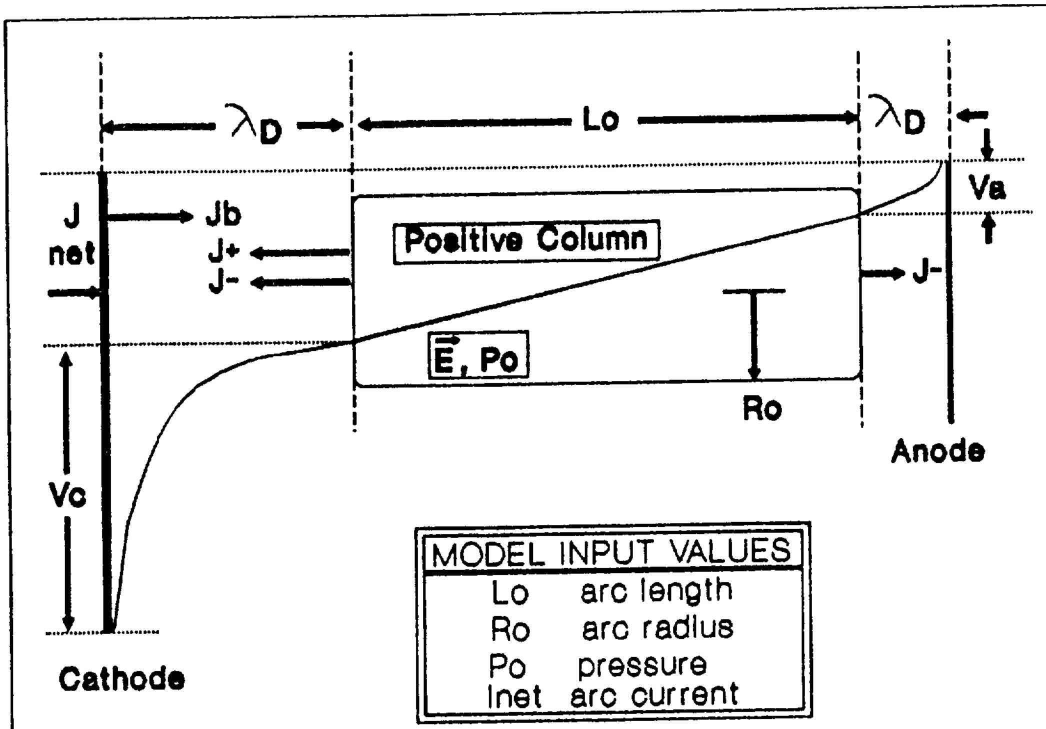

Figure 1. Simple arc model voltage distribution.

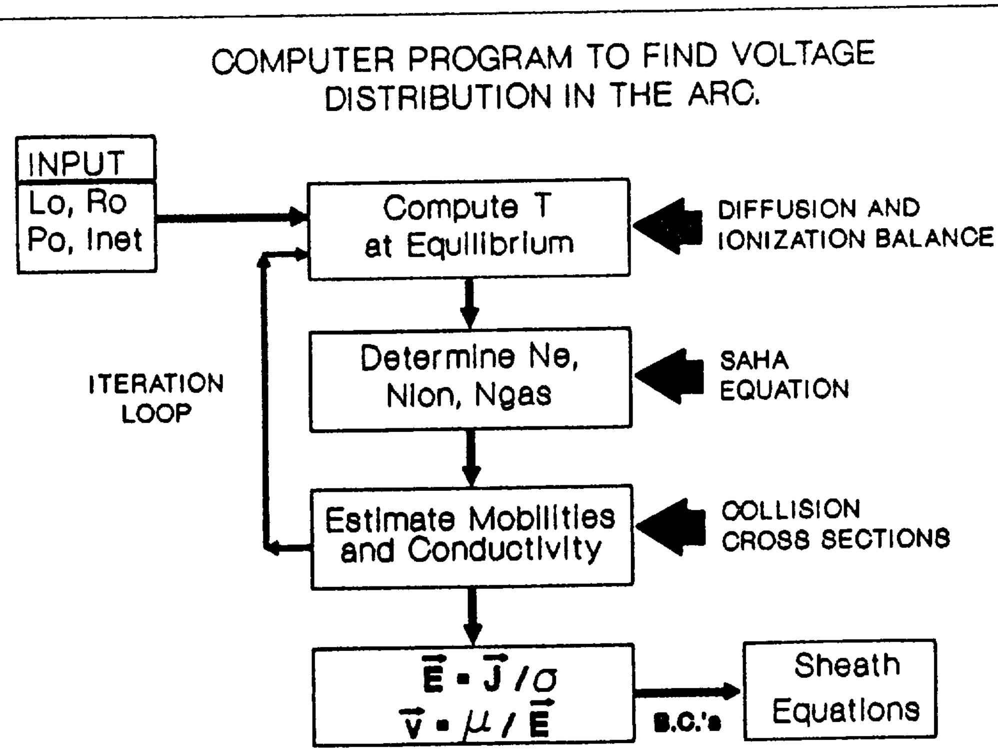

Figure 2. Block diagram of arc model program.