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Scaling of non-linear effects in heat transfer of a continuously fed melting wire

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ABSTRACT

This paper performs a comprehensive scaling analysis of heat transfer in a wire melting under conditions typical of Gas Metal Arc Welding and similar processes. This formulation includes the typical conduction and Joule heating effects, but also considers heat losses by convection and radiation and non-linearities in the thermal and electrical properties of the wire. Different regions in the wire are identified, expressions for the heat flux through the wire are developed, and the typical regime of operation is identified. Scaling laws are obtained and verified against a numerical model.

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1. Introduction

The analysis performed in this investigation is relevant for estimating the amount of heat lost by the formation of a droplet during welding. This value is essential for mathematical models of broader scope used in the analysis of metal transfer in consumable electrode welding. While numerical and closed-form models for heat transfer in the droplet already exist [1–13], a limiting factor to generalize the results has been the lack of a good closed-form model for the wire that accounts for the very large variation of thermal properties in the solid. This paper aims at closing this gap. Ultimately, these calculations will be helpful for estimating vaporization from the molten metal droplet at the end of the consumable electrode and the associated generation of welding fumes, the estimation of alloy alteration due to vaporization, and the heat content of the droplet, which influences weld penetration and phase transformations during cooling. These results have implications on the weld characteristics, performance, and operator safety during consumable electrode welding.

Numerical solutions to this non-linear problem are well known [14–16]. Analytical solutions to the linear problem considering only conduction, advection, and Joule heating are available [17–23]. There has even been an attempt to capture the non-linear effects in closed form [13]. In this case, an additional parameter is introduced into the closed form solution to the linear case; however, there are no explanations or references for the origin of the correction introduced, and only values for selected steels are presented. This results in ambiguity regarding how the relevant analysis is applied to other electrode materials.

There has been debate in the field of welding whether the variation of thermophysical properties with temperature significantly affects the temperature profile in the electrode extension, even suggesting that the expected sudden jump in temperature near the melting tip could be mainly due to non-linear effects. In this work we show that this sudden increase in temperature is due to conduction effects, mathematically captured in a boundary layer type of formulation. The role of certain non-linear effects is to modify the temperature profile relative to the linear case, thus influencing heat transfer in the electrode. Through scaling analysis it is further shown that radiation and convection to the ambient are of secondary importance.

The methodology employed in this research relies on improved scaling analysis [24–27] and numerical modeling. The two analysis techniques are first applied independently, and then are merged as necessary to improve the results of the scaling analysis, which does not require solution of non-linear differential equations. This allows easy incorporation of the results into models of larger scope and opens up the possibility of using the results in real-time welding power supply control, as the algebraic expressions obtained are more quickly evaluated than solutions to non-linear differential equations.

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Nomenclature

A	cross sectional area of wire material
A_k	non-normalized coefficients for governing equation
$f_\alpha(H^*)$	scaling function for thermal diffusivity
$f_\rho(H^*)$	scaling function for electrical resistivity
h	convective heat transfer coefficient
H	enthalpy in the wire material
I	welding current
L	electrode stickout
M_k	coefficients for resistivity correction
$N_{j,k}$	normalized coefficients for governing equation
q	wire heat flux at droplet/wire interface
r	radius of cross section of wire material
T	absolute temperature in the wire material
T_∞	absolute temperature of environment surrounding the wire
U	wire feed velocity
x	distance along wire from the molten drop

Greek symbols

α	thermal diffusivity of wire material
β	curvature parameter of enthalpy profile
$\Delta\alpha$	maximum change in α
$\Delta\rho$	maximum change in ρ
$\Delta\rho_1$	change in ρ from H_0 to H_m
$\Delta\rho_2$	related to curvature in $\rho(H)$
ε	emissivity of the wire material
ρ	electrical resistivity of wire material
σ	Stephan–Boltzman constant

Subscripts

c	characteristic value
j	term related to Component $j = 1,2$
k	refers to the kth term of an equation
m	evaluated at the melting temperature
max	maximum value of a property
min	minimum value of a property
0	evaluated at the temperature of the contact point

Superscripts

$*$	normalized function
$+$	improved estimation

Accents

$\widehat{\ }$	estimated value

2. Problem definition

To introduce the system being considered, Fig. 1 shows the feeding of a consumable welding electrode toward the left at a velocity U, while the coordinate system is stationary. The region of interest in this research is the solid portion of the electrode between the point of electrical contact and the liquid droplet formed near the arc. Above the physical schematic is a schematic of the enthalpy (temperature) profile developed along the electrode during welding. Note that the solid–liquid interface has been assigned to correspond with $x = 0$ and the point of electrical contact has been assigned to correspond with $x = L$. The underlying goal of this work is to quantify the heat q conducted from the droplet (at $x = 0$) into the electrode.

2.1. Assumptions and restrictions

When modeling complex physical phenomenon such as arc welding processes, it is necessary to make certain assumptions and impose certain restrictions to make the problem tractable. The critical assumptions and restrictions included in this research are presented here.

First, the system is treated as operating in pseudo-steady state. The Gas Metal Arc Welding (GMAW) process is clearly a dynamic process, as demonstrated by the frequent detachment of molten droplets. However, to simplify analysis, it is assumed that the effects of each individual droplet on welding parameters and welding geometry are insignificant to the purpose of this paper. Thus transient effects are assumed to average out over time, and average welding parameters and geometries can be imposed. This analysis does not, however, apply to highly transient occurrences such as arc starts and arc extinguishments.

Second, the system is assumed to be one-dimensional (in the longitudinal direction). This implies that only changes along the length of the electrode, and not those across its cross-section, are considered. This restriction necessarily precludes consideration of a microscopic electrical contact area at the contact tip. While this issue is relevant in other areas of research (contact tip life and contact resistance), it is not critical for this research. In addition, due to this assumption and that of a pseudo-steady state, transient electromagnetic effects are not considered and are treated as negligible. 1-D analysis is also unable to capture the radial variation of the solid–liquid interface in the wire. This is expected to cause only small errors in globular and projected spray transfer modes, where distinct droplets larger than and smaller than the electrode diameter, respectively, detach axially from the electrode. However, the definition of electrode extension becomes ambiguous in streaming spray mode, where the solid electrode adopts a tapered tip morphology that is coated with a thin film of liquid, which leads to formation of a liquid tail from which droplets detach. Therefore, care should be used in applying this analysis to systems operating in streaming spray mode.

Third, the model assumes a sharp, well-defined melting point on the wire. The model therefore cannot capture the effect of a mushy region that exists in the melting of electrode materials with a finite melting range. However, because of the large temperature gradient at the tip of the electrode, the temperature range over which the mushy region exists corresponds to a very small length in the electrode tip, and this effect is expected to cause only small errors.

Finally, the model assumes that thermal diffusivity and electrical resistivity vary with temperature, but does not consider how the temperature dependence of density (as manifested in the thermal diffusivity) affects the geometry of the problem. This restriction should have only a minor effect, while its inclusion would require a much more complex numerical model. In addition, the temperature dependencies of emissivity and the coefficient of convective heat transfer are ignored and generalized for all alloys. Because their effect is negligible, this too is reasonable restriction that is justified within this paper.

2.2. Applications of the modeling approach

This work relies on decoupling of the electrode from other influences, such as droplet fluid phenomena and arc heating phenomena. This is in contrast to, for example, the approach taken by Jaidi and Dutta where electrode melting is coupled with the Lorentz field to predict fluid flow and heat transfer in the weld pool [28]. Decoupling of the electrode does not imply that these

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