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Modeling the transient heat transfer for the controlled pulse key-holing process in plasma arc welding

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ABSTRACT

It is essential to model the transient heat transfer phenomena during the controlled pulse key-holing plasma arc welding (PAW) for practical application of this novel process. In this paper, a three-dimensional transient model is developed to analyze the periodic changes of the temperature field, weld pool and keyhole shape and dimensions during the controlled pulse key-holing process. An adaptive, combined, and volumetric heat source is proposed for the numerical analysis of the temperature fields in PAW process. The force action at the weld pool surface is considered to calculate the keyhole shape inside the weld pool. The dynamic variation features of weld pool and keyhole shape in a pulse cycle are numerically simulated. The phenomena of "one keyhole in each pulse" and periodic partial-open keyhole transformation are quantitatively simulated. Experiments are conducted to validate the numerical simulation results. The calculated weld cross-section is consistent with the measured ones. The predicted information on the dynamic evolution of the temperature profiles, weld pool and keyhole geometry is useful for optimizing the multi process parameters in the controlled pulse key-holing PAW process.

1. Introduction

When the high density energy from a plasma arc strikes the workpiece surface, it can immediately melt material and create a molten liquid pool (weld pool). Because of its high velocity and the associated momentum, the plasma arc can penetrate through the molten pool and form a keyhole in the weld pool. Moving the welding torch and the associated keyhole will cause the flow of the molten metal surrounding the keyhole to the rear region where it re-solidifies to form a weld bead. This is the plasma arc welding (PAW) process operating in keyhole-mode, usually referring to as the keyhole PAW for short. In keyhole PAW, the quality of the weld depends on the keyhole stability, which itself depends on the heat transfer and fluid flow phenomena inside the weld pool. However, keyhole state is sensitive to the variation of the welding conditions, and the appropriate process parameter-window is narrower to gain better weld joint quality. This limits its wide applications in manufacturing, especially for welding medium thickness plates [1]. To overcome the shortcomings, a controlled pulse key-holing system is developed for implementing keyhole PAW with lager process tolerance [2,3]. During this new process, the welding current waveform with two slow-dropping sub-stages and variable slopes are employed to actively make the keyhole behaviors vary dynamically and periodically. This so called "controlled pulse key-holing" strategy can further improve the weld quality and process stability, and widen the suitable processing parameter-window [2]. However, the new process involves more pulse parameters. It requires deep understanding of the thermal phenomena during the controlled pulse key-holing process to optimize the process parameters. Therefore, developing a transient heat transfer model is essential for correlating the pulse current parameters to the process stability and weld quality.

Though many investigators have developed quite a few models for heat transfer in welding, most of them are concerned with gas tungsten arc welding, gas metal arc welding and laser welding [4–7]. For plasma arc welding, Keanini and Rubinsky developed a quasi-steady state three-dimensional finite element model to calculate the weld pool shape and temperature fields, but the keyhole shape was assumed according to experimental results [8]. Nehad established a model for transient two-dimensional heat transfer problems during PAW process based on a presumed circular shape of keyhole [9]. Wu et al employed a combined heat source model to determine the temperature field and weld pool geometry in keyhole PAW with indirect consideration of keyhole effects [10]. All these models are for continuous current PAW process. Till to

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