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Effects of different activating fluxes on the surface tension of molten metal in gas tungsten arc welding

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ABSTRACT

Surface tension is an important factor in arc welding and affects weld microstructure and flow mode in the weld pool. A novel surface tension measurement method based on the principle of weld pool oscillation is proposed to sense the surface tension of the weld pool without and with TiO_2, NaCl, and CaF_2 activating fluxes during tungsten inert gas welding process. Experimental results reveal that the TiO_2 activating flux can convert the surface tension gradient from negative to positive but exerts minimal effect on arc behavior. The surface tension gradient is mainly controlled by the oxygen content in the weld pool, which determines the Marangoni convection and penetration depth. High oxygen content decreases the surface tension gradient and weakens the Marangoni convection in the weld pool. The NaCl and CaF_2 activating fluxes can reduce the absolute value of average surface tension but exert negligible effects on the sign of surface tension gradient. The varied surface tension and increased penetration depth with NaCl and CaF_2 activating fluxes are caused by arc constriction and increased arc temperature, respectively.

1. Introduction

As a significant physical property parameter of molten metal, surface tension plays an important role in the thermal processes of metal, such as casting, metallurgy, and welding, which are directly related to crystal nucleation and growth, phase transition, and interface/surface motion [1]. Hence, reliable obtaining the precise data of surface tension is still a long-term task for thermal processes of metal.

Several methods, such as maximum bubble pressure [2], sessile drop [3], and oscillating drop methods [4] etc., have been adopted in the past few years to measure the surface tension of molten metal. The maximum bubble pressure and sessile drop methods have been widely and successfully used in casting and metallurgy processes due to their simple equipment and principle [5]. However, both methods can only be used in limited conditions, such as steady state, equilibrium, and narrow temperature range, which greatly restrict their application in high-temperature metallic alloy, undercooled or superheated molten metal, and some special heat sources (arc plasma) etc. In addition, the measured surface tension is easily affected by small amounts of impurity because the sample (molten metal) must be in contact with the substrate or container during the measurement process. Unlike the maximum bubble pressure and sessile drop methods, the oscillating drop method using electromagnetic levitation is suitable for measuring high-temperature, superheated, or undercooled molten metal. No chemical reaction occurs between sample and container; thus, the superheated or undercooled state of molten metal is easily achieved, and wide temperature can be applied to the method [6,7]. The principle of oscillating drop method is based on Rayleigh's theory, which does not require density value to calculate surface tension. Hence, this method has higher accuracy than that of maximum bubble pressure and sessile drop methods. However, the high cost of apparatus and rigorous equipment conditions, such as vacuum and microgravity, significantly restrict its application in actual thermal processes of metal.

Arc welding, as a widely used welding process, plays an irreplaceable role in the manufacturing industry. Under the heat of arc, the base metal partially melts and forms a pool of molten metal called weld pool. The pool surface is covered with hot arc plasma during the welding process. A strong interaction exists between pool surface and arc plasma. The temperature distribution in the weld pool is extremely irregular. The above features prevent all existing surface-tension-measuring methods from being applied in actual welding process. The lack of reliable surface tension data in welding process has severely restricted the understanding of

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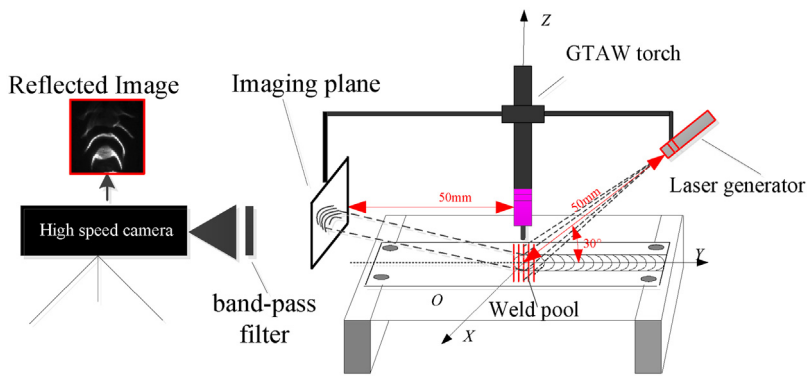

Fig. 1. Sensing system.

many scientific issues, such as flow mode of the weld pool, stability of droplet transfer, and numerical simulation of weld pool behavior etc. Especially in the activated flux tungsten inert gas (A-TIG) welding process, the mechanisms of penetration increase with activating flux are still disputed. The two mechanisms for the effect of activating flux on weld penetration are arc constriction [8,9] and reversal of surface tension gradient [10]. The mechanism of arc constriction implies that the activating flux can induce arc constriction during A-TIG welding, which increases the heat density at the anode root area, thereby increasing penetration depth. The mechanism of reversal of surface tension gradient indicates that surface active elements (SAEs), such as oxygen and sulfur, which are decomposed from activating flux during the welding process, convert the surface tension gradient from a negative to a positive value and change the direction of fluid flow in the weld pool. However, the experimental conclusions of arc constriction remain inconsistent even under similar welding conditions because the arc plasma is easily affected by various experimental conditions, such as arc length, welding speed, and shielding gas [11,12]. Many researchers have used numerical simulation to investigate the effect of reversal of surface tension gradient on weld penetration and found that the variation in surface tension gradient can greatly change the shape of weld bead [13,14]. However, the surface tension data used in numerical simulation are obtained in thermal equilibrium condition. The interaction between activating flux and pool surface and arc plasma is ignored, which causes the simulation results to relatively differ from the actual welding process. Therefore, understanding the effect of activating flux on the surface tension of molten metal during A-TIG welding process is crucial.

In this study, a novel dynamic surface tension measurement method for TIG welding based on the principle of the weld pool surface oscillation is proposed. The surface tension with TiO_2, NaCl, and CaF_2 activating fluxes and arc behavior are measured. The mechanisms for the effects of different activating fluxes on average surface tension and penetration depth are analyzed.

2. Theoretical model and sensing system

2.1. Principle of weld pool oscillation

Weld pool oscillation is the free vibration of pool surface when excited by external force. In stationary TIG welding process, the oscillation of the weld pool in partial penetration can be regarded as a free-surface standing wave [15,16]. The relationship among angular frequency ω, wavelength λ, and surface tension γ can be expressed by the following equation:

$$\omega^2 = (gk + \frac{\gamma}{\rho}k^3)\tanh(kh) \quad \text{with} \quad k = \frac{2\pi}{\lambda} \tag{1}$$

where ρ is the density of molten metal, and h is the weld depth. Two assumptions are established for Eq. (1). First, the molten metal is incompressible and inviscid. Second, the effects of the non-uniformity of molten metal on density and surface tension are ignored. Hence, the density and surface tension in Eq. (1) represent average values.

Generally, λ ∼ O(d) and λ/h > 1/3 exist in partial weld pool, which lead to

$$\tanh(kh) \to 1 \quad and \quad gk \ll \frac{\gamma}{\rho}k^3 \tag{2}$$

The relationship between the oscillation frequency of weld pool f and weld width W can be approximated as

$$\omega^2 = \frac{\gamma}{\rho}k^3 \quad \text{or} \quad f = 5.84(\frac{\gamma}{\rho})^{1/2}(W)^{-3/2} \tag{3}$$

Hence, the surface tension of the weld pool can be calculated by using Eq. (3).

2.2. Sensing system

The oscillation frequency could be hardly sensed because of a small pool surface displacement. A laser vision method, first proposed by University of Kentucky's Zhang et al. [17,18], is applied to measure the oscillation frequency of the weld pool. The sensing system diagram is shown in Fig. 1. This sensing system consists of illumination laser light, imaging plane, and high-speed camera. The illumination light is used to generate a five-line pattern and projected onto the entire possible weld pool surface. The imaging plane placed at a known distance is used to intercept the reflected laser line pattern captured by a high-speed camera.

3. Experimental detail

Pulsed TIG welding is applied to trigger the pool surface into oscillation. A welding torch with a standard 2% thoriated tungsten electrode (with a diameter of 2.4 mm and a tip angle of 60°) is used with electrode negative polarity. The shielding gas is pure argon. The base metal is stainless steel with a thickness of 5 mm. The composition of the stainless steel is Fe–0.013C–0.53Si–1.61Mn–0.017P–0.011S–19.67Cr–0.08Mo–9.95Ni–0.005Al–0.11Cu–0.046V–0.019Ti–0.072Co (wt.%). The welding parameters are shown in Table 1. The size of weld beads is changed by the arc time. Three different activating fluxes, namely, TiO_2, NaCl, and CaF_2, are used. The fluxes mixed with acetone are coated on the weld bead before welding. After welding, the weld bead is sectioned along the diameter direction. The weld width and penetration depth are observed by using an optical microscopy.