MEASUREMENT OF SURFACE TENSION OF MOLTEN METALS IN ARC WELDING

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ABSTRACT

Many reports have been shown that the buoyancy, electromagnetic force, surface tension, and gas shear stress are the driving forces of weld pool circulation in arc welding. Among them, the surface tension of molten metal plays an important role in the flow in weld pool, which are clarified by the specially designed experiments with small particles as well as the numerical simulations. The surface tension is also related to the penetration in arc welding. Therefore, a quantitative evaluation of surface tension is demanded for the development of materials and arc process control. However, there are few available data published on the surface tension of molten metals, since it depends on the temperature and the composition of materials.

In this study, a new method was proposed for the evaluation of surface tension and its temperature dependence, in which it is evaluated by the equilibrium condition of acting forces under a given surface geometry, especially back surface. When this method was applied to the water pool and to the back surface of molten pool in the stationary gas tungsten arc welding of thin plate, following results were obtained. In the evaluation of surface tension of water, it was shown that the back surface geometry was very sensitive to the evaluation of surface tension and the evaluated value coincided with the surface tension of water. In the measurement of molten pool in the stationary gas tungsten arc welding, it was also shown that the comparison between the surface tension and temperature distribution across the back surface gave the temperature dependent surface tension. Applying this method to the mild steel and stainless steel plates, the surface tension with negative gradient for temperature is obtained. The evaluated values are well matched with ones in the published papers.

KEYWORDS

Arc welding,, Weld pool, Surface geometry, Surface tension, Temperature dependence

1. Introduction

It is empirically known that the penetration in arc welding changes its shape and depth with welding conditions and material compositions. Various studies have been done to clarify the penetration phenomena and to develop the high efficiency arc welding process. As shown in Fig.1 schematically, however, the arc welding process is a very complex process, in which the arc plasma and molten metal in the weld pool interact each other. So far the investigation has been conducted on two areas, independently. One is the experimental analysis and simulation of arc plasma. Another one is the investigation of weld pool circulation. Concerning with weld pool, many reports have been shown that the buoyancy, electromagnetic force, surface tension, and gas shear stress are the driving forces of weld pool circulation in arc welding [1-8]. Among them, the surface tension of molten metal plays an important role in the flow in weld pool, which are clarified by the specially designed experiments with small particles as well as the numerical simulations [1-2]. It is also known that the surface tension is deeply related to the penetration in arc welding. Therefore, a quantitative evaluation is demanded for the development of materials and arc process control. However, there are few available data published on the surface tension of molten metals, since it depends on the temperature and the composition of materials. Recently, a quantitative measurement of surface tension is proposed. Although this method is a measurement in a vacuum chamber with a heating device, it is not applicable to the arc welding process. Because of this limitation, we propose a new method for the evaluation of surface tension, in which it is evaluated by the equilibrium condition of acting forces under a given surface

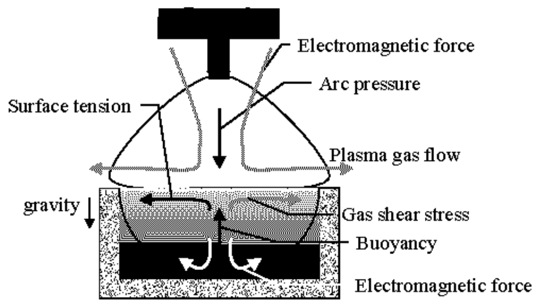


Fig.1 Schematic illustration of acting forces in arc welding

geometry. This method comes from the fact that the surface geometry is formed under the equilibrium condition of forces acting on it and the measurement of surface geometry, especially back surface, is an important technique for the precise evaluation.

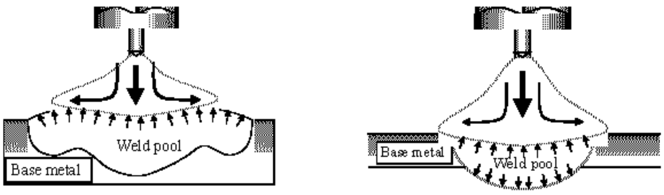
In this study, the measurements of temperature and surface geometry were carried out on the back surface of molten pool in the stationary gas tungsten arc welding of thin plate to evaluate the surface tension and its temperature dependence. Since the back surface geometry is formed so as to keep the equilibrium state among the atmospheric pressure, hydrodynamic pressure and surface tension, this relation with the measured surface geometry calculates the surface tension. In addition, the comparison between the surface tension and temperature distribution across the back surface gives the temperature dependent surface tension. Applying this method to the mild steel and stainless steel plates, the surface tension of steel and its temperature dependence were measured. In order to confirm the reliability of this method, the surface tension of water was also measured, from which the factors affecting the precise evaluation were discussed.

2. Experimental procedure

2.1 Experimental setup

Various methods are proposed for the measurement of surface tension of liquid. However, these methods are not applicable to the molten metal in arc welding, since the molten metal is high temperature liquid and the energy supply is required so as to keep the same molten state in the measurement. In this study, a new method is proposed for the evaluation of surface tension of molten metal, which is based upon the equilibrium condition of acting forces on the molten metal surface. Fig.2 schematically shows the forces acting on the weld pool surface in the arc welding of thick and thin plates. In the case of thick plate, partial penetration appears on the surface, where the various forces such as the arc pressure, gas shear stress, hydrodynamic pressure and surface tension influence the surface geometry. In the case of thin plate, the full penetration prepares two free surfaces in the molten pool; top and bottom surfaces. The acting forces on the top surface are same as the ones in the case of thick plate, while only the hydrodynamic pressure and the surface tension act on the bottom surface. Therefore, the surface tension is easily estimated by the measurement of bottom surface geometry. From this point of view, our attention is paid to the bottom surface for the evaluation of surface tension of molten metal. In addition, the temperature dependence of surface tension is estimated by the simultaneous measurement of temperature with surface geometry.

Fig.3 shows the experimental setup used in this study. This apparatus consists of welding device, image acquisition and temperature measurement systems of bottom surface of weld pool. The welding device is used to make the stable bottom surface of molten pool, in which stationary gas tungsten arc welding was done on 100×100×3 mm thin plate fixed on the support box with copper flame. During welding, argon gas is supplied into the support box for the prevention of weld pool from oxidation. In the image acquisition and temperature measurement system, CCD camera with VTR and the radiation pyrometer were used for the simultaneous measurements of bottom surface geometry and temperature distribution, respectively. Then, the bottom surface geometry is used for the evaluation of surface tension, which is obtained from the equilibrium condition among the hydrodynamic pressure, surface tension and atmospheric pressure. The evaluated values of surface tension were compared with the temperature distribution across the weld pool, from which the temperature dependence of surface tension is evaluated. The materials used for the evaluation of surface tension are mild steel and stainless steel.



(a) Thick plate (b) Thin plate

Fig.2 Comparison of forces on surfaces

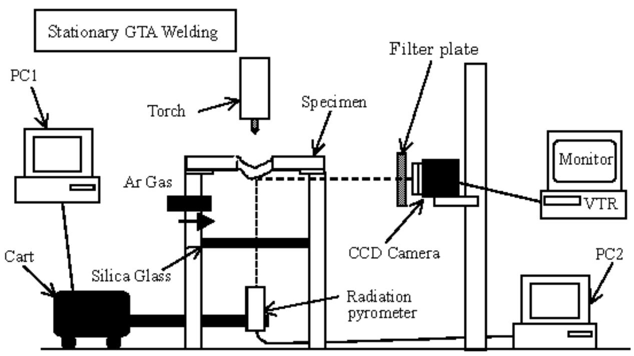


Fig.3 Experimental setup

2.2 Analysis of surface tension

Fig.4 shows the schematic illustration of acting forces on the bottom surface, in which the surface geometry is formed so as to satisfy the equilibrium condition of these forces. So, when the surface geometry is measured by the side view of the weld pool, the surface tension is given by a following equation.

$$\sigma=\rho g(z+H)/(\kappa 1+\kappa 2) \qquad (1)$$

where, σ is surface tension, $\kappa 1$, $\kappa 2$ are the curvatures in the radial and circumferential direction, ρ is the density, g is the gravity accretion, and H is constant. In this relation, the curvatures were calculated by the surface geometry and the constant H includes the effects of arc pressure and the molten metal in the plate on the hydrostatic pressure, since the surface geometry is measured by the height from bottom surface of plate. Therefore, this relation shows that the surface tension of molten metal is evaluated only by the measurement of bottom surface geometry during stationary gas tungsten arc welding of materials. In this study, this relation is also applied to the water pool hanging down from the hole in the thin plastic plate, from which the reliability of this method and the sensitive factors to the evaluation of surface tension were discussed.

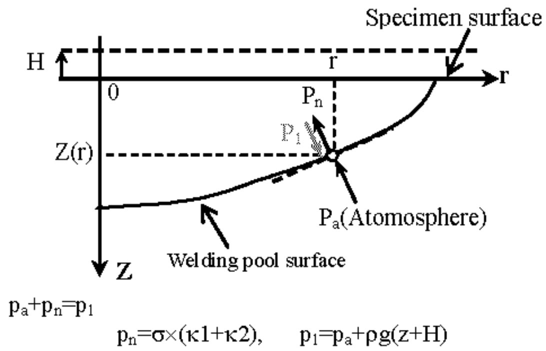


Fig.4 Schematic illustration of forces acting on bottom surface

3. Results and discussion

3.1 Surface tension of water

In order to confirm the reliability of the evaluated values of surface tension, this method was applied to the water pool. Fig.5 shows the appearance of water pool hanging down from the hole in the plastic plate. This water pool is formed in the hole 5mm in diameter of the plastic plate 1.8 mm in the thickness. It is seen that this water pool is almost axis symmetrical and shows a similar shape to the weld pool in the arc welding. Fig.6 shows the bottom surface geometry of the water pool, which is obtained from the image in Fig.5. In order to apply the proposed method to this water pool, this geometry was approximated by a polynomial function using a least squares method, which is represented by a solid line in the figure. Fig.7 shows the surface tension of water, which is evaluated by the substitution of the polynomial function into equation (1). It is noted that the surface tension shows almost constant values across the pool, although there exist extremely high values at the center and edges. In addition, the evaluated values indicate a little lower value than the surface tension of pure water, which is represented by straight line in the figure. It was also shown that same values of surface tension were obtained from the weld pools with different diameters, regardless of different bottom surface geometries. A little lower value than the surface tension of pure water and the extremely high values at the center and edges are caused from following reasons.

Fig.5 Appearance of water pool

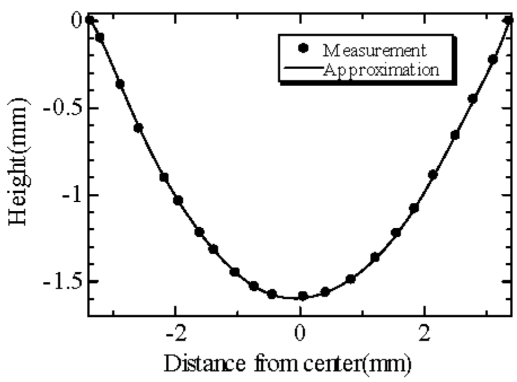


Fig.6 Bottom surface geometry

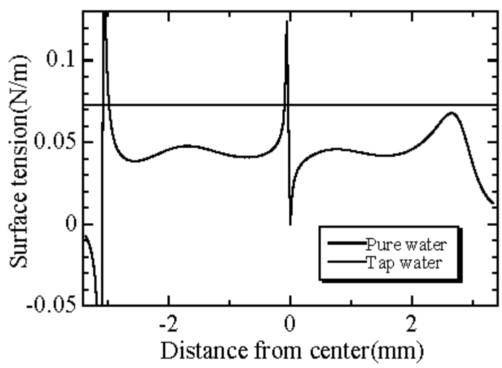


Fig.7 Surface tension of water

- Extremely high values at center and edge: This is caused from the polynomial approximation of surface geometry. That is, a slight difference between the polynomial approximation and the true surface geometry occasionally causes the curvatures to be small values, which results in a extremely large value since the equation for the evaluation of surface tension contains the curvatures in the dominator. Therefore, the extremely high surface tension in Fig. 7 indicates that the polynomial approximation in Fig.6 contains a slight deviation from the true bottom surface geometry at the center and edge of the water pool.
- A little lower values than surface tension of pure water: There may be two possibilities for this reason, which are the dissolved materials in the water and the effect of constant H in the calculation. First one is the use of tap water, which contains various dissolved materials such as detergent, sterilizer, and contaminants in the vessel. Since these materials decrease the surface tension, the dissolved materials are considered to be a main reason for a little lower value than the pure water. The effect of constant H was also discussed. In this measurement without the effect of arc pressure, the constant H is equal to the water thickness in the plastic plate. Since the plastic thickness is 1.8 mm, the effect of constant H on the surface tension was investigated in the range from 1 to 1.8 mm. Fig.8 shows the effect of constant H on the evaluation of surface tension. It is seen that a slight change is observed in the evaluated value of surface tension, but its effect is minor.

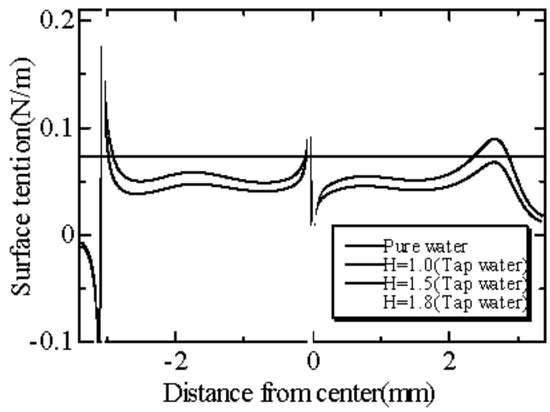


Fig.8 Effect of Constant H on surface tension

From these results, a proposed method is shown to be available to the evaluation of surface tension of liquid. However, following considerations are required in the measurement.

- Acquisition of clear image of bottom surface: Since a proposed method is based upon the equilibrium condition of the forces acting on the surface and surface geometry is related to the hydrodynamic pressure, clear image is demanded for the precise measurement of surface geometry.
- Polynomial approximation of surface geometry: In the evaluation of surface tension, the calculation of curvatures is required. Since the second derivative of surface geometry is contained in the curvatures, a slight deviation from the true geometry results in the large difference in the evaluation.
- Formation of pool with axis symmetrical shape: This is also related to the calculation of curvatures. If the shape of bottom surface is axis symmetrical, the calculation of curvatures is simplified. Therefore, a special attention was demanded in the arc welding of materials.

3.2 Surface tension of molten metal

BasedBased upon the results obtained from the measurement of water pool, this method was applied to the weld pool in the stationary gas arc welding to evaluate the surface tension of molten metal.

Fig.9 show the image of bottom surface of weld pool. This image was taken at 500 seconds after the arc starts on the mild steel plate with the welding condition of 90 Ampere in welding current. Since the arc light is very strong and the image is acquired by CCD camera through filter plate, it becomes a little dark image. However, the contour of weld pool is recognized together with slag at the outer area. Then, the bottom surface geometry could be measured with aid of image processing technique. Fig.10 shows the bottom surface geometry. It is noticed that the weld pool indicates almost symmetrical shape in respect to the centerline and coincides with a polynomial approximation. When the equilibrium condition is applied to the surface geometry, the surface tension is obtained. Fig.11 shows the distribution of surface tension across the weld pool. In this case, the extremely high surface tension also appears at the center and right edge. It is also noticed that the outer area with steep decrease of surface tension corresponds to the area covered with the slag. Nevertheless, the surface tension in the area from 2 mm to 5 mm is in the range from 1.7 N/m to 2.0 N/m, which are well matched with 1.8 N/m in the published report. In this study, the temperature distribution was also measured by radiation pyrometer. Fig.12 shows the temperature

Fig.9 Image of bottom surface of weld pool

distribution on a line across the weld pool. It is seen that the temperature in the area within 5 mm in radius is about 1500°C and steeply decreases in the outer area. In addition, a slight lower temperature at the center is an interesting phenomenon, which seems to be related to the metal flow in the weld pool. Since, as clarified in the previous report [8], there exists the sub-flow due to the down flow from the top surface to the area 5 mm in radius, a little lower temperature and the maximum temperature appear at the center and at the area 5 mm in radius, respectively. When this temperature distribution is compared with the surface tension, the relation between the surface tension and temperature is obtained, which is shown in Fig.12. In this figure, it is noticed that the surface tension increases with temperature in the range below 1400C, while it decreases with temperature in the range over 1400°C. As mentioned above, the surface tension in the low temperature region below about 1400°C includes the influence of slag and the evaluated values are not the surface tension of molten metal. Therefore, it is concluded that the evaluated values in the temperature range above 1400C is available and its temperature dependence is given by a negative gradient. This tendency was confirmed by the experiments with different time, plate and welding condition. The measurement was also applied to the stainless steel plate. Although similar results were obtained in the stainless steel, the evaluated values were scattered because of a lot of slag and a little distorted shape of weld pool.

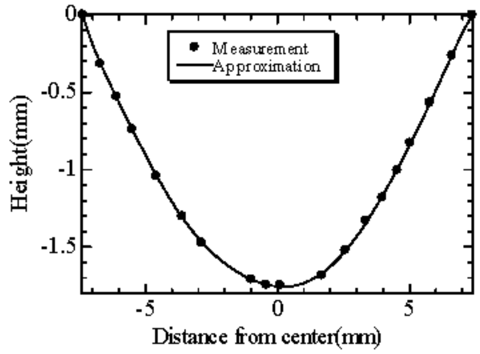


Fig.10 Bottom surface geometry of weld pool

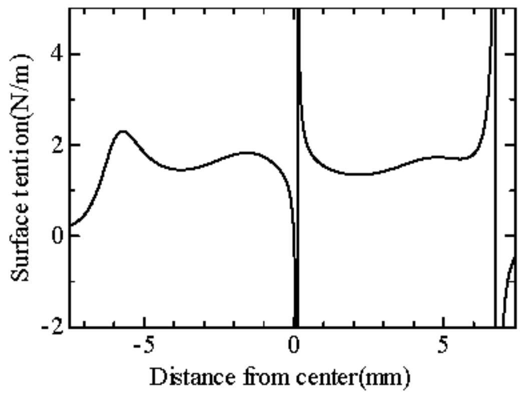


Fig.11 Distribution of surface tension

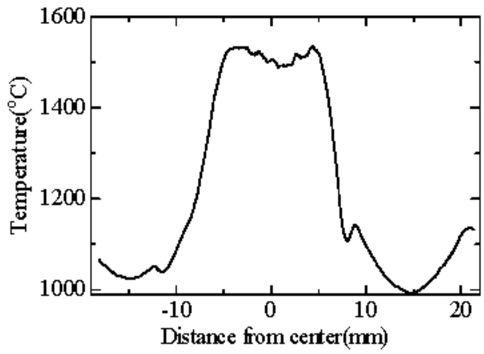


Fig.12 Temperature distribution of bottom surface

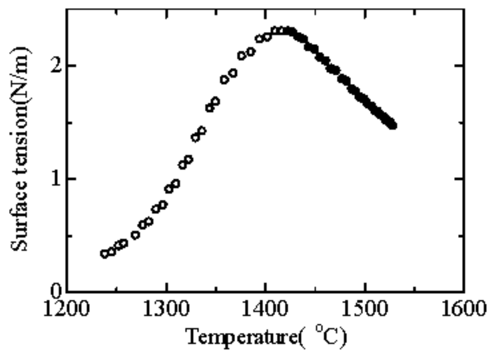


Fig.13 Relation between surface tension and temperature

4. Conclusions

In this study, a new method for the evaluation of surface tension was proposed, which is based on the equilibrium condition of acting forces on the back surface of molten pool in the stationary gas tungsten arc welding. This method was also applied to the water pool to clarify the reliability. The main results obtained are as follows.

1) A method based upon the equilibrium condition of acting forces on the back surface of molten pool was available to the evaluation of surface tension of molten metal. The measurement required for the evaluation is only the surface geometry.

2) A measurement of water clarified that the critical factors in the evaluation were precise measurement and polynomial approximation of surface geometry. The evaluated values of water were reasonable ones and suggested that the proposed method was applicable to the measurement of surface tension of molten metal.
3) The comparison between the surface tension and temperature distribution across the back surface gave the temperature dependent surface tension. Applying this method to the mild steel plates, the surface tension with negative gradient for temperature was obtained. The evaluated values were well matched with ones in the published papers.

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