Fluid and arc behavior with ultra high frequency pulsed GTAW*

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During ultra high frequency pulsed gas tungsten arc welding (UHFP-GTAW), the root radius of arc decreased with arc constriction that caused the narrower weld bead. The larger arc force created the more depression of surface, which had been important to increasing of weld penetration. Simultaneously, molten liquid metal is the key factor during welding process, and the mobility of molten pool was enhanced by weld behavior compared with conventional gas tungsten arc welding (C-GTAW). In the paper, the characteristics of arc behavior and fluid of molten pool was discussed with UHFP-GTAW. The results indicated the significant effect of the arc plasma on heat and force of molten pool with UHFP-GTAW. Further, the temperature diffusion of molten pool would reduce, which can limit the impact of arc heat on base metal effectively.

Key Words: Ultra high frequency pulsed arc, fluid in molten pool, arc behavior, ultra speed camera

1. Introduction

The welding current has huge effect on arc behavior, especially with pulsed arc welding 1). Pulsed frequency has significant effect on arc profile, arc force and penetration. With ultra high frequency pulsed-arc welding (UHFP-GTAW), the root radius of arc decreased with arc constriction that caused the narrower weld bead. And the fluid and geometry of molten pool are very important for weld appearance, microstructure and mechanical properties 2-3). The larger arc force created the more depression of surface, which was important to weld penetration 4-5). Simultaneously, molten liquid metal is the key factor during welding process, and the mobility of molten pool was enhanced by weld behavior compared with conventional arc welding (C-GTAW) 6). The visual research on arc plasma and fluid in molten pool is necessary for the mechanism study with pulsed arc welding. Such phenomenon needs to observed, which is very crucial for discussing dynamic process of welding arc and fluid in molten pool with various arc welding modes. In recent years, significant progress has been made in understanding the complexity of the physical processes in fusion welding. Particularly, modeling and vision sensing have provided significant insight into the dynamics of the welding processes. The numerical models have gone a process from planar surface to deformed surface, from steady state to transient state, from two dimensions to three dimensions. Furthermore, some investigators consider the numerical treatment of the arc and the molten pool independently 7,8), and the others propose a coupled model of them 9-10). The two types of models are distinguished by whether to consider the interaction of the arc and weld pool. In the former case the properties of the arc are applied as boundary conditions for the molten pool and it assumes no mutual influence between the arc and the weld pool. Sensing technology is an important component in automatic welding. It enables visualization of the welding process, which has not observed accurately and comprehensively before. The sensors can even transform the electromagnetic field, temperature field, force field, flow field into visual representation 11). More information captured by the method would provide an access for deep understanding and comprehensive analysis of the complex multi-physics coupling and interactions.

In this paper, the visual system was established for arc profile and molten pool. The characteristics of the arc behavior and the fluid of molten pool will be described with UHFP-GTAW, which will also be compared with C-GTAW. The methods with experiments and theoretical study are produced for the important factors. And the fluid in the surface of molten pool is monitored to predict the fluid velocity that is the supplement for further study. The results indicated the significant effect of the arc plasma on heat and force of molten pool with UHFP-GTAW.

2. Experimental procedure

2.1 Welding Experiments

C-GTAW was set as the contrast experiment group. UHFP-GTAW was carried out with current up/down slope rate (di/dt) more than 50 A/µs that were achieved with insulated gate bipolar transistor (IGBT) switch component. The schematic diagram and actual welding current were illustrated in Fig.1, respectively. Where, \(I_b/I_p\) was background/pulsed current and \(f\) the pulse frequency. Time of background and pulsed currents were \(t_b\) and \(t_p\), respectively. The conventional parameters were as follows:

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the electrode radius was 1.2 mm and made of 2% cerium and 98% tungsten; the arc length was 3 mm; the gas was 99.99% argon. 0Cr18Ni9Ti stainless steel (h=5mm) was picked up.

2.2 Visual observation

Fig. 2 illustrated the fluid observation system. During welding, the arc plasma and camera remains stationary. The movement of workpiece is completed by X direction moving apparatus. The main component was established with Mega Speed Camera (MS75k, full maximum capture frequency is 6kHz), filter lens, and light reduction lens of adjustable wide-angle. Combination use of lens will be carried out for high-quality figure or video. The thermal imager was used for temperature surveillance illustrated in Fig.3. The dynamic process of welding temperature was captured.

3. Result and discussion

3.1 Arc behavior

Ti-6Al-4V was used to study arc profile with different welding methods. Welding speed was set as 150mm/min. Compared with C-GTAW, root radius of UHFP-GTAW decreased by 7% at least, and obvious arc constriction can be found. When pulsed frequency increased, arc constriction tended to be significant. With 80kHz, the root radius reduced by 24% at most.

According to the Ampere law, the current beam with the same direction will create self-excited magnetic field in space. The magnetic field can create Ampere force with mutual attraction that is called electromagnetic force. It is believed as the reason for pinch effect. With DC welding, directional movement of charged particles (positive ions and electrons) create a stable current in arc plasma. Furthermore, the radial electromagnetic force is the key factor for arc contraction. The effect of electromagnetic force can be illustrated in Fig.5. \( F_e \) is electromagnetic force, and \( F_{rel}/F_{ral} \) is radial/axial element of \( F_e \) respectively. \( r_0/R \) is radius in top/root surface. \( \theta \) is the angle between arc edge and molten surface, and \( l \) means the arc length.

The radial element is represented in Eq.1. Variables substitution is
carried out \((n=R/r_0)\), and two variable functions \((f_1, f_2)\) were found in Eq.2. Thus, \(F_{er}\) can be represented with product of variable functions. With the arc constriction, the root radius decreased with \(F_{er}\):

\[
F_{er} = \frac{\mu}{4\pi} \frac{r^2}{R} \ln \frac{R}{r_0} \frac{1}{R-r_0} \quad \text{Eq.1}
\]

\[
\begin{cases} 
  f_1 = \ln n \\
  f_2 = 1/(n-1)
\end{cases} \quad \text{Eq.2}
\]

The experimental results indicated the average root radii are 3.02mm, 2.77mm, 2.60mm, and 2.39mm at C-GTAW, \(f<40kHz\), 45~65kHz, and \(f>70kHz\), respectively. Radius in top surface \(r_0=1.20mm\). Thus, the variable functions \(f_1, f_2, f_1\times f_2\) can be calculated. From the description above, \(f_1\times f_2\) represent \(F_{er}\). Setting C-GTAW as the reference value, variation of \(f_1\times f_2\) can be calculated. The attenuation coefficient of electromagnetic force \(\psi\) is defined with Eq.3 to evaluate \(\Delta F_{er}\). The results of calculation are listed by Tab.1.

\[
\psi = |\Delta(f_1\times f_2)/(f_1\times f_2)|_{f=0} \quad \text{Eq.3}
\]

where, \(\Delta(f_1\times f_2) = (f_1\times f_2)_{f=0} - (f_1\times f_2)_{f=0} \).

<table>
<thead>
<tr>
<th>Pulsed frequency (f/kHz)</th>
<th>Avg root radius (R_{avg}/mm)</th>
<th>(f_1\times f_2)</th>
<th>Coeff. (\psi%/)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>3.02</td>
<td>0.611</td>
<td>0</td>
</tr>
<tr>
<td>(&lt;40)</td>
<td>2.77</td>
<td>0.641</td>
<td>4.9</td>
</tr>
<tr>
<td>45~65</td>
<td>2.60</td>
<td>0.665</td>
<td>8.8</td>
</tr>
<tr>
<td>70~80</td>
<td>2.39</td>
<td>0.693</td>
<td>13.4</td>
</tr>
</tbody>
</table>

When \(f<65kHz\), the average \(\psi\) was less than. And it was when \(70~80kHz\). Previous work indicated the stable status exist during 45~65kHz. With, the dynamic balance of arc plasma was broken and root radius decreased again that was illustrated in Fig.6.

3.2 Molten fluid

Molten fluid on the surface of molten pool was studied with stainless steel and the average welding current was 70A. With C-GTAW, fluid on the surface of the molten pool was displayed in Fig.7, and the capture was underway with moving arc. The time interval is 0.02s, and the fluid process can be found. The fluid flew from center to front, then separated to both normal directions of moving arc. Some parts were pushed to the edge of molten pool with oxide film (0.02s). Others flew to the back of molten pool rapidly (0.04s), and the solidification process happened at the edges as resistance of liquid-solid interface (0.06s).

Fluid velocity can be evaluated with the movement of oxide film on the surface of molten pool. The locations with different time were marked in Fig.8 and the distance between internal can be obtained respectively. The travelled distance during the interval was used to calculate the velocity. The average velocity of impurities was 15.76cm/s and the edge location owned larger velocity than that in the center of molten pool. However, it is the average velocity of impurity that was stopped by flow resistance. As a result, the max velocity of surface fluid was predicted to be much more than 16cm/s. The future work of molten behavior will focus on the differences between C-&UHFP-GTAW. Particle tracer will be carried out for checking the mode of fluid and status on the surface of molten pool. Accurate velocity will be predicted. The model with same current will be produced and the simulated value can support the experiments.
3.3 Thermal process

With Ti-6Al-4V, the dynamic temperature distribution can be captured that was illustrated in Fig.9. The average welding current was 60A with C-GTAW, and 30A of background current and 60A of pulsed current during UHFP-GTAW.

![Temperature distribution at initial time](image)

The temperatures at initial time are almost the same, however, the heat affect area can be found much different. With UHFP-GTAW, the distribution area reduced significantly in Fig.9b, c. All the figures were captured just before moving, and the molten pool had been found under the arc. The waiting times for molten pool forming were 20s, 13s, and 10s, respectively, which inferred large arc heat density with UHFP-GTAW. More, during the moving process, the top temperatures were at least 100K higher than C-GTAW. The above result can be due to arc constriction during pulsed welding, which caused large energy density for the arc.

4. Conclusions

Ultra speed camera and thermal imager were used for visual welding process. The arc profile and fluid on the surface can be captured dynamically. During UHFP-GTAW, significant arc constriction can be found with increasing pulsed frequency. Thermal tests indicated the temperature distribution area reduced compared with C-GTAW. High top temperature and welds were caused by large arc energy density with UHFP-GTAW.

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Reference