



Weld penetration sensing in pulsed gas tungsten arc welding based on arc voltage



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ABSTRACT

An alternative to the conventional weld penetration sensing methods in pulsed gas tungsten arc welding is proposed for implementation at manufacturing sites. The fluctuation amplitude of arc voltage in the peak duration (ΔU_k) reflects the weld penetration status in a single-weld spot; a fully penetrated weld spot is obtained in the step-by-step welding process when the abrupt change of ΔU_k (denoted as $\Delta U'_k$) is above the threshold (1.50 V herein). A full penetration control system that employs $\Delta U'_k$ as the feature signal for step-by-step pulsed gas tungsten arc welding can be easily installed at the manufacturing sites.

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1. Introduction

Medium-thickness steel plates, namely steel plates with thickness ranging between 4.5 mm and 25 mm, are usually used in structure construction, machinery manufacturing, container manufacturing, and so on. However, it is difficult to guarantee the welding quality for medium-thickness steel plates, especially the root pass. The penetration of the root pass, and therefore the final weld quality (e.g., mechanical properties and life time of the joint) (Fan et al., 2003), is affected by the good cooling condition of medium-thickness steel plates in the welding process and by the unfavorable welding conditions, such as misalignment of workpieces and uneven gaps between these plates. One of the effective methods frequently used for root pass welding is gas tungsten arc welding (GTAW). Because of the low heat input of GTAW, an automatic full penetration control at the manufacturing sites is important.

The first step in the automatic weld penetration control is to find a feature signal that can be obtained and processed in real time to characterize the weld penetration status. Several techniques such as temperature measurement, imaging, acoustics, and X-ray have been proposed to determine this condition. Fan et al. (2003) studied the changes in temperature distribution surrounding the weld pool using an infrared sensor to detect different workpiece

inclination angles that have a significant influence on the weld penetration depth. Vasudevan et al. (2011) developed a computer-controlled GTAW machine that enables sensing of weld pool using an infrared camera mounted on a torch assembly. They revealed that an inverse linear relationship exists between the macroscopic temperature gradient, computed from the infrared thermal profile, and the measured penetration depth for the weld bead. Unfortunately, the results of infrared thermography are influenced by radiations from the arc and tungsten, the variation of the weld pool surface slope, and emissivity. Moreover, the infrared cameras are expensive and fragile under harsh conditions at the manufacturing sites. Chen et al. (2009) developed a welding robot system including two function modules (visual and data acquisition modules) and its corresponding software system. From the top view, they measured the weld penetration depth in the welding of aluminum alloy; however, the images were affected by strong arc light, and only the weld pool profile could be obtained. The depth of weld pool in two-dimensional images, which is considered as the most important information for weld penetration control, could not be extracted and applied. Saeed et al. (2004) proposed a technique for measuring the three-dimensional (3D) weld pool surface from specular reflection of laser beams, by using a simulated environment and a mathematical model for 3D surface measurement. This method could only be applied to the GTAW process in which the weld pool is relatively stable and its surface slopes are small. Furthermore, image processing, which utilizes concepts of optical flow, structured light, and feature point tracking, is complicated. Zhang et al. (2006) proposed a structured light method to visualize the

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weld pool in GTAW using the specular property of the weld pool and eliminating the effect of the strong arc; however, the reconstruction of the weld pool was complicated (Song and Zhang, 2007); moreover, the method was applied in gas metal arc welding (Ma and Zhang, 2009). Mnich et al. (2004) developed a method for sensing 3D weld pool information using binocular vision; however, in this method, the arc hinders obtaining information about the geometry underneath the torch, the synchronization of two cameras is rigorous because of the dynamics of the weld pool surface, and the reconstruction algorithm is difficult and complex because of the lack of features on the weld pool surface. As can be seen, all the 3D vision methods of weld pool are usually constricted by complex computation, which makes it difficult to use them in real time at manufacturing sites. Tao et al. (2014) investigated acoustic emissions to detect welding porosity and incomplete penetration. They distinguished two types of welding defects using the amplitude and centroid frequency of acoustic emissions. The acoustic emission technique used at manufacturing sites requires noise-reduction methods and an efficient and fast data processing system when welding defects are encountered. Guu and Rokhlin (1989) developed a computerized radiographic weld penetration control system, in which weld pool depression is used as feedback. The X-ray systems are expensive and well-designed radiation protection systems should be installed at manufacturing sites for the sake of safety of the workers.

The applicability of most of the above-mentioned sensing techniques is limited under practical conditions. Therefore, to characterize the weld penetration status, electric signals (namely welding current and arc voltage), which are easily obtained and processed at the manufacturing sites, are proposed. A full penetration weld-sensing concept for medium-thickness steel plates is presented in Section 2, in which the feature signal, which is discussed in Section 3, plays the key role. A series of experiments were designed and conducted, as described in Section 4, to prove that the fluctuation of the arc voltage can reflect the weld penetration status. The experimental results are processed and discussed in detail in Section 5.

2. Full penetration welding conception

GTAW has a low heat input and thereby has a low efficiency. To obtain a larger penetration, pulse current is used, namely pulsed GTAW (GTAW-P), but a full penetration weld cannot be guaranteed in a GTAW-P process. As a result, a “step-by-step welding” method is proposed, shown in Fig. 1, in which the welding torch remains stagnant at a spot until the arc heats the weld pool to achieve full penetration and then travels the “step distance” to heat up the next weld spot. In this way, a full penetration pass can be obtained as long as the step distance is reasonable and penetration sensing works well. It is apparent that the key to realize this concept is to obtain a feature signal for full penetrations at each weld spot.

3. Proposed feature signal

To mimic the behavior of a skilled welder in full penetration welding, the weld pool surface should be captured by visual sensors, which function as the eyes of the welder, and be processed by an algorithm, which works as the brain of the welder, in an automatic welding system. However, it is difficult to obtain a clear image of the weld pool surface because of the strong arc and specular reflection, as well as the feature signal from a dynamic weld pool surface. Therefore, a systematic analysis of the GTAW-P process is required for understanding different physical phenomena

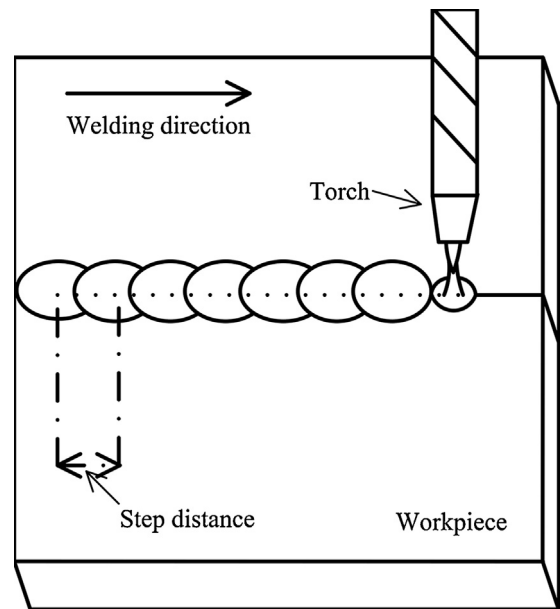


Fig. 1. Step-by-step welding.

(Zhao et al., 2004), including the weld pool surface behaviors that reflect the weld penetration status.

During welding, the shape and size of the weld pool change with the variation of arc force, heat input, and boundary constraints around the weld pool, among others. A fully penetrated weld pool shows a clear difference in the bottom boundary constraint compared to a partially penetrated weld pool, as can be seen in Fig. 2. Under the condition of full penetration, the weld pool will fluctuate intensely in the absence of the solid boundary constraint at the bottom (in liquid boundary constraint). From the point of view of weld pool growth in single-weld-spot welding, the fluctuation of weld pool will show an abrupt change at the same time when the solid boundary constraint at the bottom recedes, which also indicates full penetration of the weld spot. The fluctuation of the weld pool can be expressed indirectly by the change of the arc voltage in the GTAW-P process (as the tungsten will not be consumed in the GTAW, it can be considered as a constant constraint for arc, the fluctuation of the arc is only affected by the constraint at the side of weld pool); therefore, the abrupt change in the fluctuation amplitude of arc voltage in the peak duration ($\Delta U'_k$) is proposed to be the feature signal to identify the time when full penetration is achieved in each weld spot. If $\Delta U'_k$ acts as an effective indicator of the penetration status, the step-by-step GTAW-P system shown in Fig. 3 will function efficiently.

4. Experiment design

A series of experiments were designed and conducted in order to prove the concept presented in Section 3. The practicability of the concept and stability of the feature signal were also verified.

A fixed single-weld spot, which is representative of the weld spots in the pass, is welded by the step-by-step GTAW-P method. Although there are some differences between two weld spots in the step-by-step welding because of heat accumulation, weld penetration sensing is not affected, as discussed in Section 3.

The boundary constraint at the bottom and the arc force affect the fluctuation amplitude of the weld pool. In order to study the effect of only the boundary constraint at the bottom, the peak current (I_p) is set at a constant value (400 A) for eliminating the effect of different arc forces. To obtain the desired information in the peak duration, the base current and its duration are kept constant;

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