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Proceedings of Symposium on Ultrasonic Electronics, Vol. 35 (2014) pp. 49-50
3-5 December, 2014

Fundamental study of molten pool depth measurement method using an ultrasonic phased array system
ﾌｪｰｽﾞﾄﾞｱﾚｲ超音波装置を用いた溶融深さ測定方法の基礎検討

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1. Introduction

Nondestructive measurements during welding are important in order to improve the quality of welded structures. The surface measurement technique using a high-speed camera and an optical filter during welding has been reported [1]. Information about the molten pool depth direction is not obtainable by such an optical measurement, however. It is necessary to use an X-ray transmission imaging method or an ultrasonic measurement method to measure the materials internally. Melt flows inside the molten pool during welding have been observed with an X-ray transmission real-time imaging system [2]. The X-ray transmission method is not easily applicable to most inspection sites due to the large size of the device used. Moreover, the X-ray transmission imaging method is incompatible with measurements of the molten pool depth for a thick metal because there are few differences in the attenuation rates between the case where X-rays penetrate a molten pool and the case where X-rays do not penetrate the molten pool. On the other hand, the ultrasonic measurement device is a relatively small device and it is highly applicable to inspection sites. The conventional measurement method of the molten pool depth using a laser ultrasonic technique has been presented by a temperature distribution model [3]. However, this model needs improvement of depth measurement accuracy. The purpose of this study was to realize precise ultrasonic in-situ measurements during welding. A novel measurement method was proposed to obtain a molten pool depth. The proposed method was confirmed by measuring the molten pool depth on a flat stainless steel type 304 plate with an ultrasonic phased array system during melting with a gas tungsten arc welding (GTAW) machine.

2. Measurement method

The molten pool depth is evaluated by comparing the propagation time for the ultrasonic wave to propagate through a molten pool (liquid phase) and a solid phase and the propagation time fort the ultrasonic wave to propagate through only the solid phase near the molten pool. **Fig. 1** shows the ultrasonic propagation paths. On propagation path ‘k’, the ultrasonic wave propagates through only the solid phase type 304 near the molten pool. On propagation path ‘i’, the ultrasonic wave propagates through the solid phase type 304 and the molten pool of type 304. If the temperature of the molten pool and the temperature of the surface at the measurement points are assumed to be uniform, these two propagation paths can be expressed as a sound velocity-time graph as shown in **Fig. 2**. The area enclosed by path ‘k’ is equal to the area enclosed by path ‘i’ because of the same thicknesses of the flat type 304 plate. Therefore, the depth of molten pool is estimated using equation (1):

$$d = \frac{(\tau_m - \tau_0)(V_{Solid}(T_b) + V_{Solid}(T_m))V_{Liquid}}{2(V_{Solid}(T_b) + V_{Solid}(T_m) - 2V_{Liquid})} \qquad (1)$$

where d is the molten pool depth, τ is propagation time of the path that the ultrasonic wave propagates through the liquid phase and solid phase, τ_0 is propagation time of the path that propagates through only the solid phase, $V_{solid}(T_b)$ is the sound velocity at the surface temperature of the array probe side, $V_{solid}(T_m)$ is the sound velocity at the temperature of the boundary between the liquid phase and solid phase, and V_{liquid} is the sound velocity of liquid phase.

3. Experiments

Molten pools were formed with a GTAW machine on a 30mm thick flat type 304 plate at different fixed points for about one minute. The welding currents were (a) 70A, (b) 100A, and (c) 150A. The welding voltage was fixed at 10V. Each molten pool was simultaneously measured with the ultrasonic phased array system. A photo of the experimental setup is shown in **Fig. 3** and a schematic image of the measurement is shown in **Fig. 4**. Molten pools were measured with a 64 element 1mm pitch 2MHz linear array probe and heat resisting wedge. Experimental conditions are listed in Table 1. The linear scanning collected the reflected ultrasonic waves in 1mm steps by electrically switching 32 partially active elements of the array probe. Molten pool depth distributions were estimated from reflected waves which were recorded just before turning off the power supply of the GTAW machine for comparison to cross section observations.

4. Results

The results of the molten pool depth distribution estimated by equation (1) and the cross section observations are shown in **Fig. 5**. For the welding current of 70A, the maximum molten pool depth was evaluated as 0.5mm. For the welding current of 100A, the maximum molten pool depth was 2.1mm. And for the welding current of 150A, the maximum molten pool depth was 3.1mm. Comparing evaluation results and cross section observations, maximum molten pool depths were estimated within an error of ±0.5mm.

5. Conclusion

The molten pool depth measurement method using the ultrasonic phased array system was proposed. Molten pool depth was evaluated by comparing the propagation times for the ultrasonic wave to propagate through a liquid phase and a solid phase and the propagation time for the ultrasonic wave to propagate only through the solid phase near the molten pool. The proposed method was confirmed by measuring the molten pool depth on a flat type 304 plate during melting with a GTAW machine. Maximum molten pool depths for the different welding current parameters from 70A to 150A were estimated within an error of ±0.5mm. In the future, the proposed method is expected to be utilized to decide welding parameters.

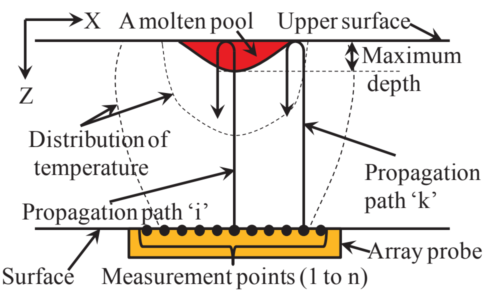

Fig. 1 Measurement model of molten pool depth

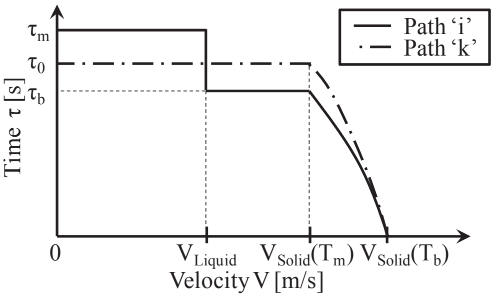

Fig. 2 Comparison of two propagation paths

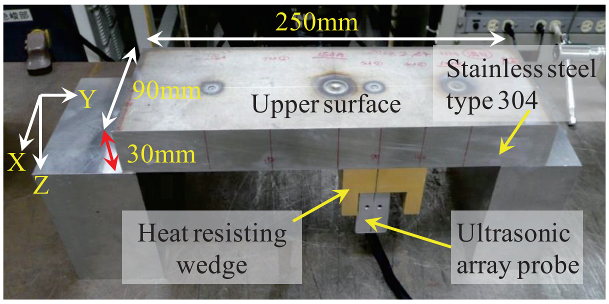

Fig. 3 Experimental setup

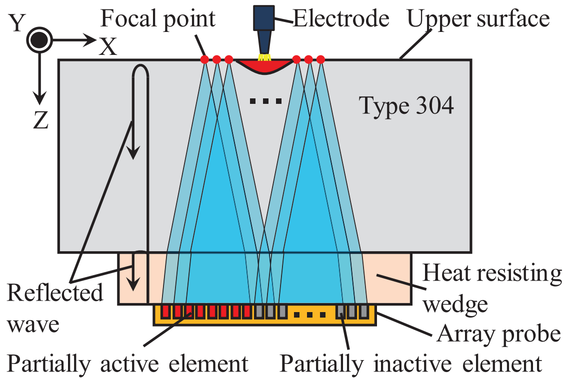

Fig. 4 Schematic image of the measurement

Table I. Experimental conditions

Linear scan	Elements	Active: 32 Inactive: 32
	Scan step	1mm
	Focal law	30mm
Pulse voltage		160V
Frequency filer		1MHz-5MHz

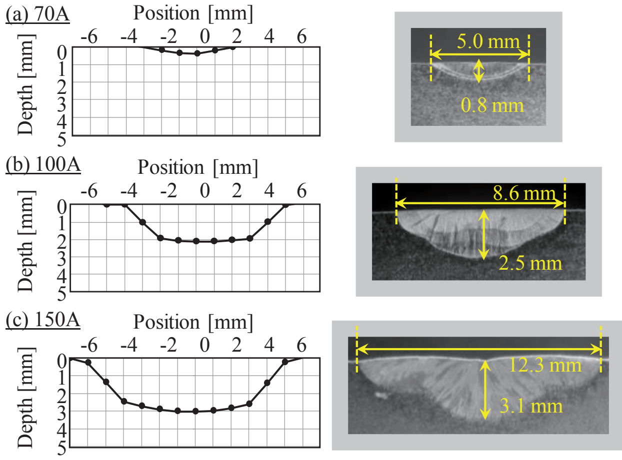

Fig. 5 Results of molten pool depth distribution and cross section observations

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