Online Measurement of the Penetration Depth in Arc Welding

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Abstract. *A measurement method is presented for automatic arc welding systems. In particular it is applicable in situations where no access to the back side of the material is possible, for instance pipes. The method is based on the oscillations of the welding pool, when subjected to a high current trigger pulse. The spectrum of the response to this pulse contains information about the penetration depth of the weld pool in the material, and can be retrieved from the arc voltage. Experimental results are in agreement with the theory, and demonstrate the feasibility of the method for industrial practice.*

Keywords: Arc Welding, Weld Pool Oscillation, Orbital Welding

1. Introduction

Arc welding is based on the creation of an electric arc between an electrode and the material to melt. The quality of the welded joint is determined largely by the weld pool geometry during the welding process, metallurgical properties of the weld material and the geometry of the materials to be welded. In order to obtain adequate strength in a welded joint, it is necessary to achieve proper weld penetration. Too little penetration results in an incomplete adhesion between the metal parts throughout the thickness of the joint, and too much penetration may produce a weak joint of the base metal with the surrounding material.

Therefore, it is important to develop techniques to analyze and sense the level of penetration during arc welding and develop control systems for automatic welding. Inspection methods that do not require access to the backside are ultrasonic sensing, surface temperature, trace element method, arc voltage variation due to surface sagging and weld pool oscillation sensing. The latter technique is described in more detail in the next sections.

2. Principle of weld pool penetration measurement

The measuring method is based on the relation between the arc voltage and the distance between the electrode and the surface of the weld pool. This distance changes with the shape of the weld pool, the latter being determined by forces acting on the pool and material flow within the pool ([1]). The basic idea of penetration depth measurement is pool oscillation. During welding, the weld pool is brought into oscillation by applying high current pulses with a short pulse time, in the order of tens of ms. The oscillation modulates the distance between the pool surface and the electrode, and hence the arc voltage at constant current. Fig. 1 shows a typical response on a trigger pulse of about 300 A, at a particular penetration depth.

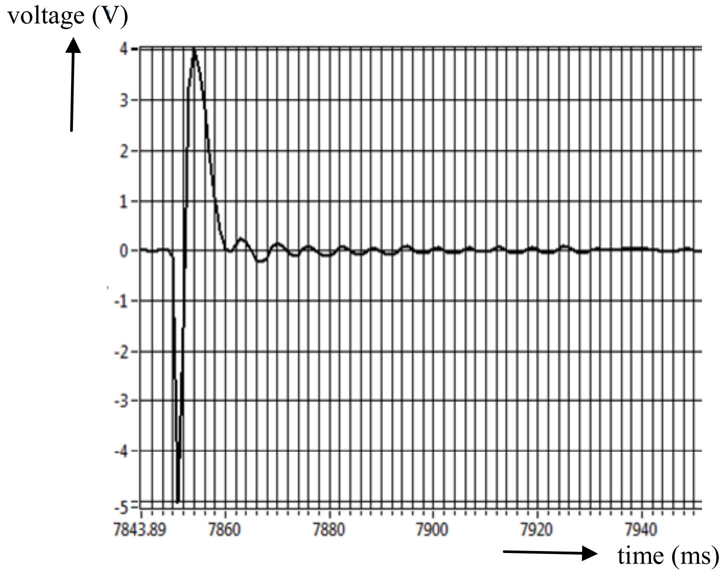


Fig. 1. Typical response of the arc voltage on a high current trigger pulse

The pulses are repeated every 0.5 to 1 s, providing information about the weld pool depth during welding. The oscillation frequency shortly after this trigger pulse is determined by the shape and depth of the weld pool as well as the material properties, see Fig.2 [2].

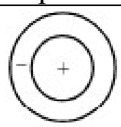
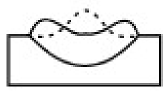
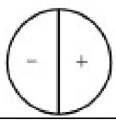
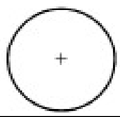
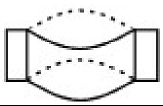
Mode	Top view	Side view	frequency
Mode 1			$f = 5.84\left(\frac{\gamma}{\rho}\right)^{\frac{1}{2}} D^{-\frac{3}{2}}$
Mode 2			$f = 3.37\left(\frac{\gamma}{\rho}\right)^{\frac{1}{2}} D^{-\frac{3}{2}}$
Mode 3			$f = \frac{1.08}{D}\left(\frac{\gamma}{\rho h}\right)^{\frac{1}{2}}$

Fig. 2. Typical response of the arc voltage on a high current trigger pulse

In this figure, γ is the surface tension in $N.m^{-1}$, ρ the metal density in $kg.m^{-3}$, D the diameter of the weld pool in mm and h is the weld pool depth in mm.

When the weld pool has just reached the bottom of the material (denoted by full penetration), the oscillation mode of the liquid metal changes from mode 1 or 2 to mode 3, which is reflected in a change in frequency spectrum of the arc voltage right after the trigger pulse, as can be seen in Fig. 3 illustrating schematically this process [3].

3. Experiments

A series of experiments on a flat plate is executed to verify the theory and to investigate the applicability in industrial practice. The arc voltage is measured by a differential amplifier, band-pass filtered and further processed by a Labview programme. For the time being the FFT is performed offline, after having completed a welding experiment. We report here about just a single experiment, with major welding parameters: base current 65 A, pulse current 350 A, pulse width 1 ms, shielding gas: argon, material: steel 304, plate thickness 3 mm. The distance between the plate and the electrode is set at 1.5 mm. The spectra of the arc voltage are shown in Fig. 4, at three instances of the process.

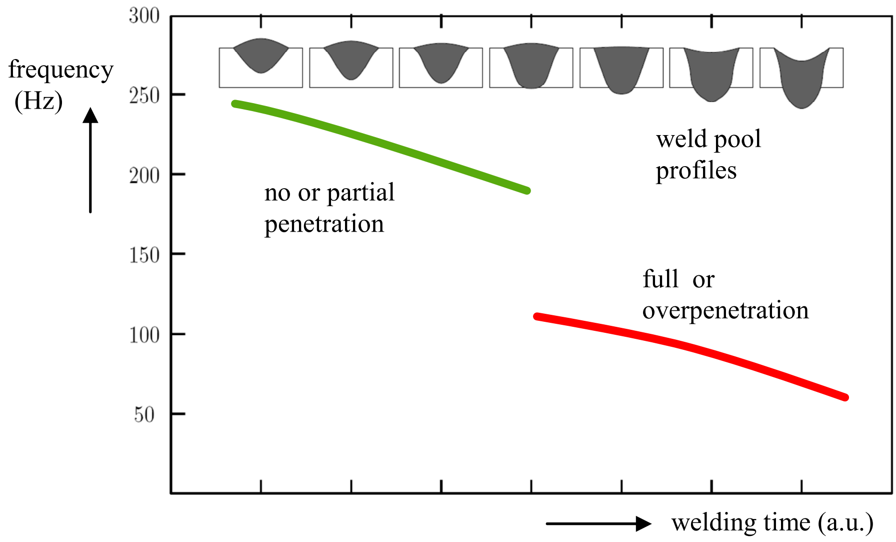


Fig. 3. Principal frequency components versus penetration (theoretical).

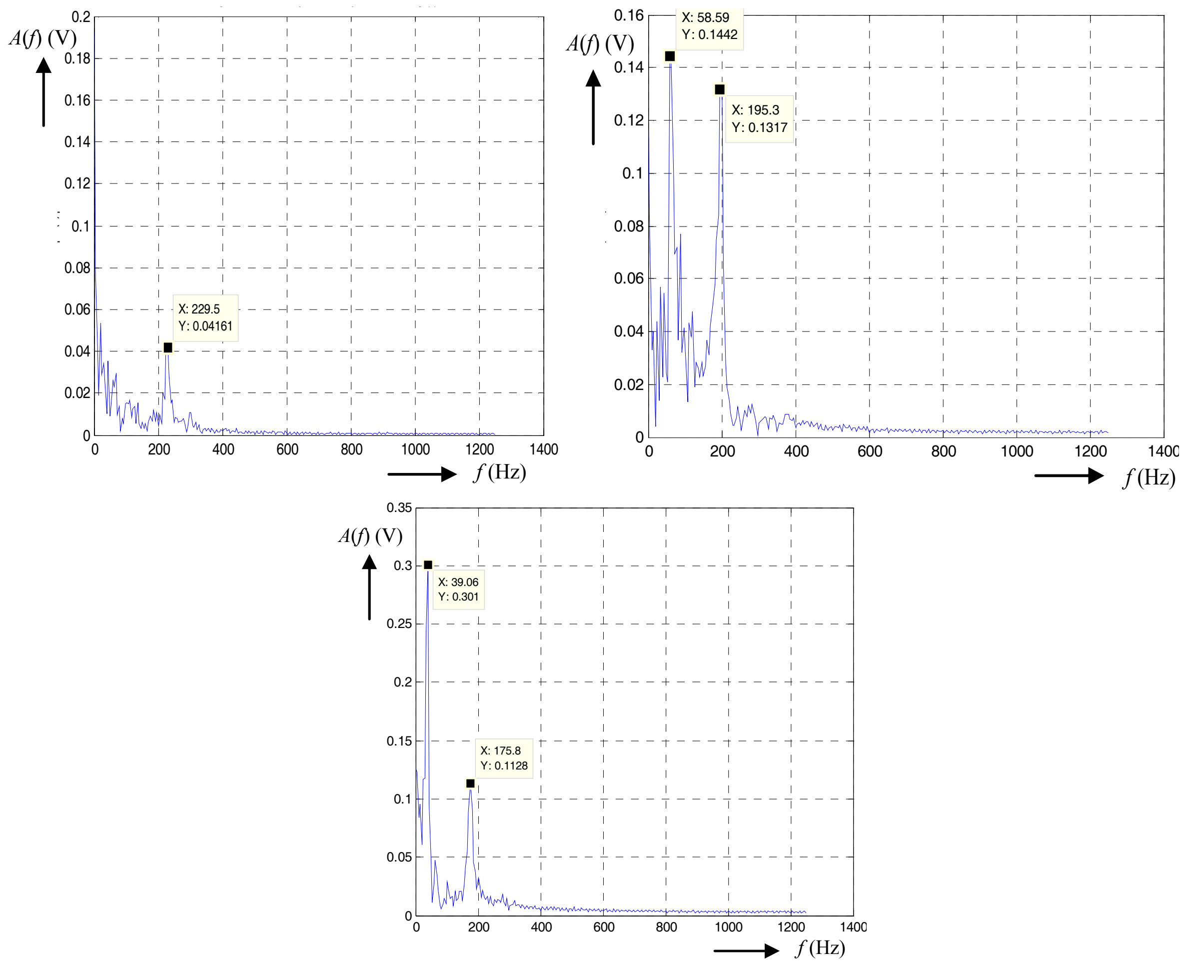


Fig. 4. Arc voltage spectrum after the 1st, 10th and 18th trigger pulse

The time window for the FFT starts just after the high peak in the response shown in Fig. 1, and has a width of about 50 s. The three pictures in Fig. 4 show three penetration stages. The first has a main peak at a relatively high frequency, in this case around 200 Hz, corresponding with partial penetration. The second one shows two peaks, around 200 and 50 Hz respectively. In the third picture the 50 Hz component dominates the spectrum. At the 10th pulse, where both frequencies are present, there is a transition from partial to full penetration, which corresponds to an optimal weld. The frequencies are in agreement with values reported in literature ([2,4]).

Fig. 5 shows the welding result of the welding experiment described in Fig. 4, corresponding to the situation after the 18th pulse. From this picture we see that full penetration has been reached indeed, and no overpenetration occurred.

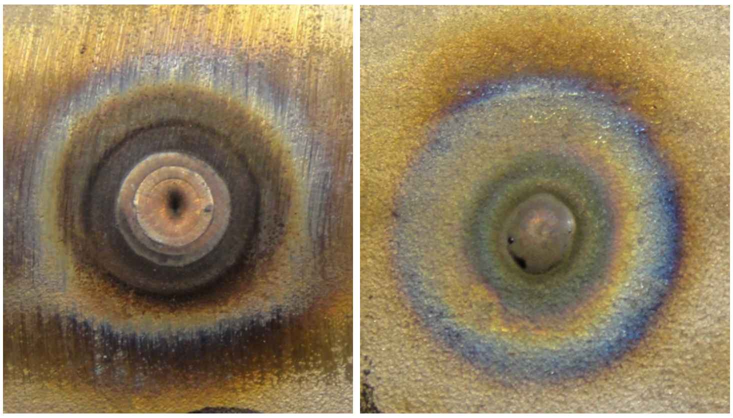


Fig. 5. Front (left) and back (right) side of the welding

4. Conclusions and further work

Many more experiments have been carried out, with different parameters of the trigger pulse, different materials and both fixed and moving electrodes. These experiments have demonstrated the feasibility to measure the moment of full penetration in a TIG welding process without the need of any additional sensors, just by analyzing the frequency spectrum of the arc voltage. This information can be used in a control system to automatically keep the penetration depth at an optimal value, irrespective of electrode distance, welding speed, material thickness and other variations.

Further research aims at the optimization of the control system and extension of the applicability to orbital welding of pipes, where online monitoring of the weld quality inside the pipe itself is impossible.

References

[1] Kou S. and Sun D.K., "Fluid Flow and Weld Penetration in Stationary Arc Welds", Metallurgical and Materials Transaction A, 16(1), pp 203-213, 1985

[2] Yudodibroto R.B.Y.B, "Liquid Metal Oscillation and Arc Behavior During Welding", Pd.D Thesis, Delft University of Technology, The Netherlands, 2010

[3] Patent pending

[4] Aendenroomer T., "Weld Pool Oscillation for Penetration sensing and Control", Ph.D. Thesis, Delft University of Technology, The Netherlands, 1996