

Dynamic behavior of the weld pool in stationary GMAW

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Abstract. Because hump formation limits welding productivity, better understanding of the humping phenomena during the welding process is needed to access to process modifications that decrease the tendency for hump formation and then allow higher productivity welding. From a physical point of view, the mechanism identified is the Rayleigh instability initiated by strong surface tension gradient which induces a variation of kinetic flow. But the causes of the appearance of this instability are not yet well explained. Because of the phenomena complex and multi-physics, we chose in first step to conduct an analysis of the characteristic times involved in weld pool in pulsed stationary GMAW. The goal is to study the dynamic behavior of the weld pool, using our experimental multi-physics approach. The experimental tool and methodology developed to understand these fast phenomena are presented first: frames acquisition with high speed digital camera and specific optical devices, numerical library. The analysis of geometric parameters of the weld pool during welding operation are presented in the last part: we observe the variations of wetting angles (or contact lines angles), the base and the height of the weld pool (macro-drop) versus weld time.

1 Introduction

Industrial applications of welding processes constantly demand productivity and quality enhancements. One such approach involves using numerical simulation and experimentation in a complementary way to improve welding operations [1]. However, numerical simulations are mainly related to a specific problem such as heat transfer and distortion predictions, so an experimental method is necessary for synchronized measurement of different parameters during welding operations and correlations with numerical predictions. Thus, the main objectives of this work were: 1) improve understanding of physical phenomena and their interactions, 2) validate numerical simulations, and 3) facilitate remote monitoring of arc welding using these results.

To illustrate this approach we have chosen a problem linked to productivity and quality for the manufacture of welded joints. For welded products, productivity increases with welding travel speed, but some welding defects related to bead shape, such as formation of bead humps and undercutting at the weld edges limit the maximum feasible travel speed. Because hump formation limits welding productivity, better understanding of the humping phenomena during the welding process is needed to arrive at process modifications that decrease the tendency for hump formation and allow higher productivity welding.

Bradstreet [3] was the first researcher to experimentally study bead hump formation in the gas metal arc welding (GMAW) process. Humping was defined as the series of undulations of the weld bead. From a physical point of view, the mechanism identified is the Rayleigh instability initiated by strong surface tension gradient which induces a variation of kinetic flow [9]. These hydrodynamic disturbances cause constrictions in the back of the weld pool. It results both in a cooling and a rapid solidification of the liquid stream that produces a boundary "solid" for the liquid metal coming upstream. A hump is formed. Cho [4] used computer simulation to provide the knowledge of heat and fluid flows leading

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to a deeper understanding of humping phenomenon during the high travel speed weld. In a first step, we present the experimental approach that we have developed to study arc welding processes (process, optical, thermal and numerical libraries BAME, erCv for analysis). Because of the phenomena complexity, we then chose to conduct an analysis of characteristic times involved in the behavior of weld pool in pulsed stationary GMAW [5–8], using this experimental approach. The goal is to simplify a future modeling process for a detailed understanding of the phenomenon of humping.

2 Experimental methods

We developed an accurate, reliable and synchronized measurement system in the highly noisy environment of Gas Metal Arc Welding [2].

2.1 Experimental approach

To analyse efficiently welding and characteristic times, it is necessary to measure different kind of signals. Welding induced high degree of perturbation due to electromagnetic noise and radiation due to the arc. The high gradients induced by the plasma in the workpiece let conventional local measurement hazardous. Nevertheless, field measurement (Classical and Infrared imaging) needs to be coupled to some other measurements to have sense. Global measurements (current, arc voltage,...) give informations on the level and the evolution of input/output in the welding process.

Because of the different natures of the acquisition combined with the large amount experimental tests to analyze, the design of a library to treat experimental datas and images was thought as well as their coupling. As explained by Todoroki [11], it could be tedious to manage several files from different natures. For example electrical acquisition in the generator is performed around several of kHz whereas mechanical acquisition is performed around several Hz. Because welding is highly hostile for any kind of pointwise measurement, non contact field measurement with high speed camera is a good tool to analyse mechanism for example metal transfer in the arc [10]. This means several kHz acquisition frequency that lead for 3s of images to 2Goctets file. Measurements of different kinds at high frequency could not be used with software management. Hardware synchronisation is then emphasized.

A rigorous analysis of experimental tests needs some calibration tests that must be kept to fully analyze the experiments. Combination of direct measurement with calibration for large amount of channels could be error-prone if made manually. Managing errors in datas acquisitions needs to be automated in order to be fully confident in the measurement.

To manage set of datas could also be tedious if acquisition is performed without any cautions and if information relative to the test are lost. In order to render easy the treatment and the analysis of the datas, a data structure for the test was designed in order to quickly find informations and values of sensors. For the welding application, the datas are split into five different types :

- Process : arc voltage - current - gas flow - wire speed;
- Mechanic : strain gage, displacement, force;
- Thermal : thermocouple;
- Cameras : High speed camera and near infra red camera;
- Geometry : geometrical characteristics of the specimen.

These kinds of measurement are given as an example and are not exhaustive at all. All these measures will not be enough to describe the process and some additional information must be stored. It is important to know which process is studied, which metal want to be joined and which gas is used in order to capitalize all kind of datas. All these static datas must be retrieved and could be used to discriminate experimental tests.

The BAME¹ library is developed in generic and oriented-object framework to allow the management

¹ Numerical library open source : <http://subver.lmgc.univ-montp2.fr/BAME>
developed by welded assemblies team, LMGC UMR 5508 - UM2 - CNRS

of all the datas generated during a process test. Genericity imposes some requirements and concepts to the design and object oriented allow to make reusable and extensible code.

The configuration of the devices could influence the software implementation. To be the most versatile and adaptive to every kind of acquisition device (new camera or new sensors), the choice was made to let all devices be independent. An overview of the experimental setup is given in Fig.1 and some particularities are outlined.

The experimental setup is divided into four parts (i) the welding process including generator and torch, (ii) the XY robots, (iii) Sensors and conditioner and (iv) the personal computer. Sometimes a camera could be used with its standalone computer.

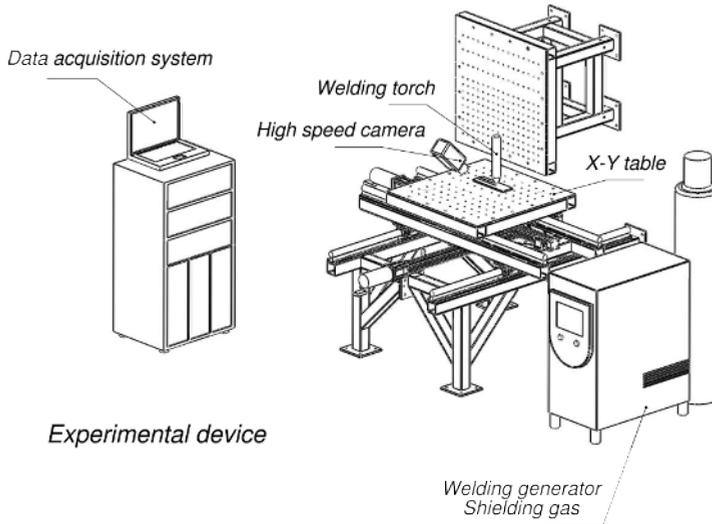


Fig. 1. Experimental device.

2.2 Experimental procedures

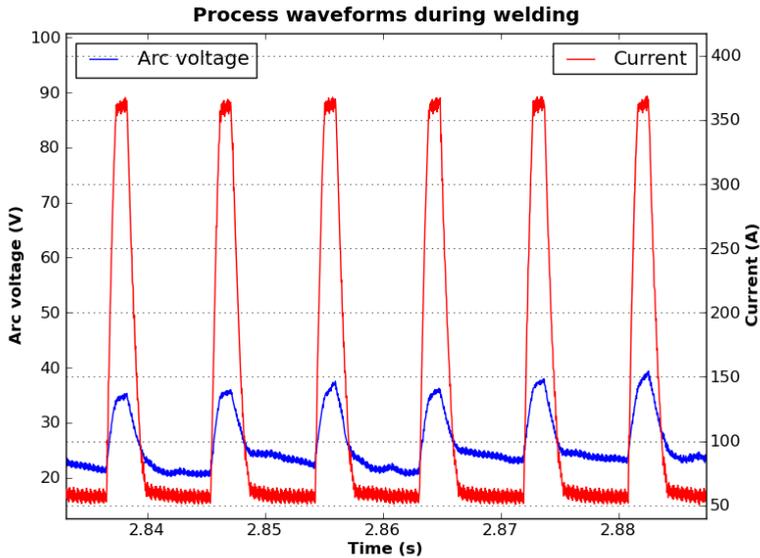
Stationary spot welds were made using the Pulsed Gas Metal Arc Welding process (Oerlikon CitoWave 500) to observe non isothermal spreading of weld pools. The target is a steel disk (thickness = 15 mm) and ER70S steel welding wire were used for welding experiments. The welding duration was 3.5 s. Welding parameters were set values summarised in Table 1. Our experimental approach (see section 2.1) was used to synchronise the high speed camera images, the process parameters and thermocouples acquisitions. Welding current and arc voltage were recorded at 30kHz sampling rate. Examples of acquired current and voltage waveforms are given in Fig.2, in adequation with welding parameters given in Table 1. The temperature history at several locations (20 and 30mm from the center of metal deposit), was measured with thermocouples of 0.6 mm diameter Type K wires, glued with epoxy to the plate surface. A high speed camera (Phantom V5.0) with a back lighted shadowgraphic method recorded weld pool images at a rate of 4000 frames per second so that weld pool radius and apparent liquid solid external contact angle histories could be measured.

A $650 \pm 10nm$ band pass filter was used to attenuate arc light for clear images of weld pool growth and weld metal transfer. Measurements of weld pool dimensions were made using the erCv² library. This library is specially developed for the analysis of the weld pool geometry.

² Numerical library open source : <http://subver.lmgc.univ-montp2.fr/erCv>
developed by Edward Romero, LMGC UMR 5508 - UM2 - CNRS

Table 1. Summary of welding parameters used in experiments.

Weld time (s)	3.5
Wire feed speed (cm.min ⁻¹)	6.
Welding wire type	ER70S
Wire diameter (mm)	1.
Contact type to work distance (mm)	20.
Shielding gas	92%Ar - 8%CO ₂ .
Shielding gas flowrate (l.min ⁻¹)	18.
Peak current (A)	370.
Background current (A)	70.
Pulse time (ms)	2.
Pulse frequency (Hz)	125.

**Fig. 2.** Arc voltage and current waveforms acquired during welding.

The erCv library was designed to facilitate the measures of the characteristic parameters (geometries and times) of evolution of a weld pool, with huge flows of processed images (up to 30,000 frames per test). An example of weld pool measurements using erCv is shown in Fig.3.

With the profile of the weld pool, we can determine the geometric parameters reflecting its dynamic behavior (such as Fig.4).

3 Results & discussions

The presented results are about the dynamic behavior of the weld pool in P-GMAW. In first time, we look only the evolution of the geometrical parameters versus weld time. With this analysis, we wish to arrive to a first understanding of the weld pool behavior.

3.1 Datas acquired

Sequences of high speed camera images are shown in Fig.5. We observe the spreading kinetic of the weld pool, from the beginning of the formation of the macrodrop to the arc extinction and the

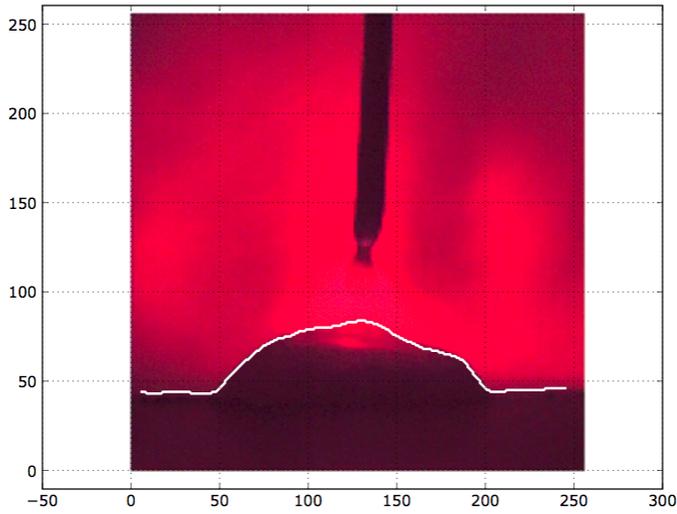


Fig. 3. Weld pool measurements using erCv; Units of axes : pixels. The white curve represents the profile of the drop automatically detected.

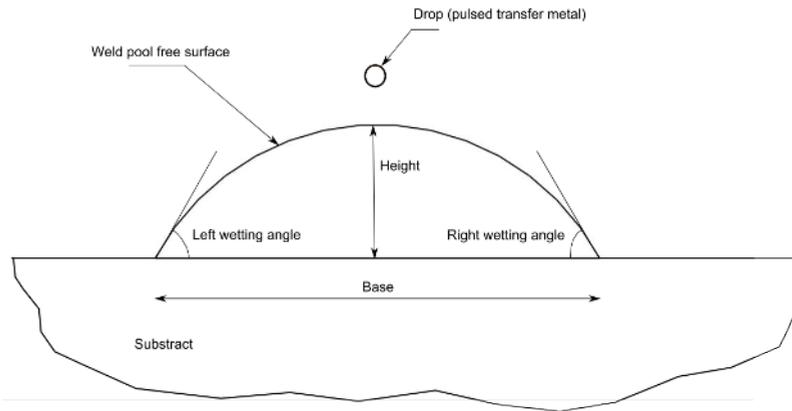


Fig. 4. Geometric parameters of the macrodrop.

solidification ($\approx 4s$). During initial weld times, video images showed that the base measurements fluctuated due to short circuiting and erratic globular metal transfer. After 1.s, the experimental pulsed arc was stable and droplets were deposited into the weld pool with a frequency of 125 Hz. The acquired images cannot be identically filtered during the experiment, leading thus to difficulties in the further automatic treatment by the erCv library.

3.2 Datas analysis

In Fig.6, the deposit base of weld pool obtained with erCv video measurements is plotted vs. weld time. According to experimental result the deposit base increased rapidly at the beginning of the weld. This is presumed to correspond to rapid spreading of the solidus isotherm on the substrate surface by direct arc heating allowing spreading of the molten metal deposit. The spreading quickly transitions to

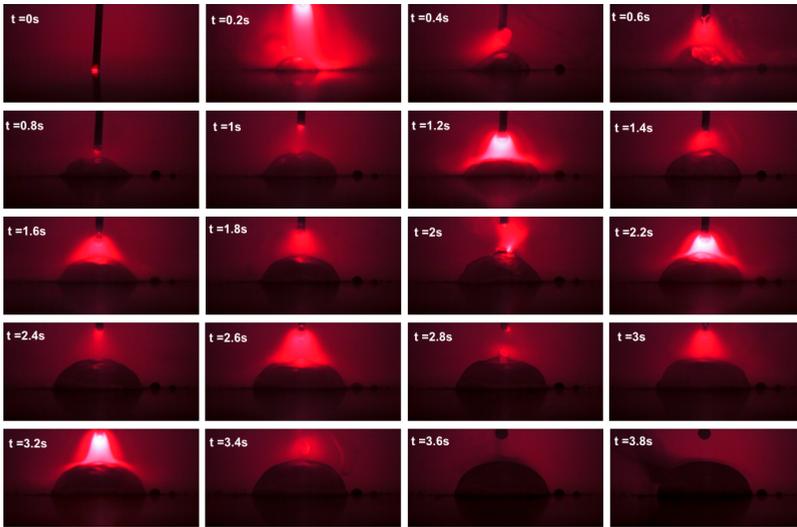


Fig. 5. Macrodrop frames acquired during welding. Times 0 to 1s correspond to short circuiting and erratic globular metal transfer, times 1 to 3.8s to pulsed metal transfer in the weld pool.

a more gradual increase. In the experimental deposit base curve, the initial molten metal base quickly reached 8 mm.

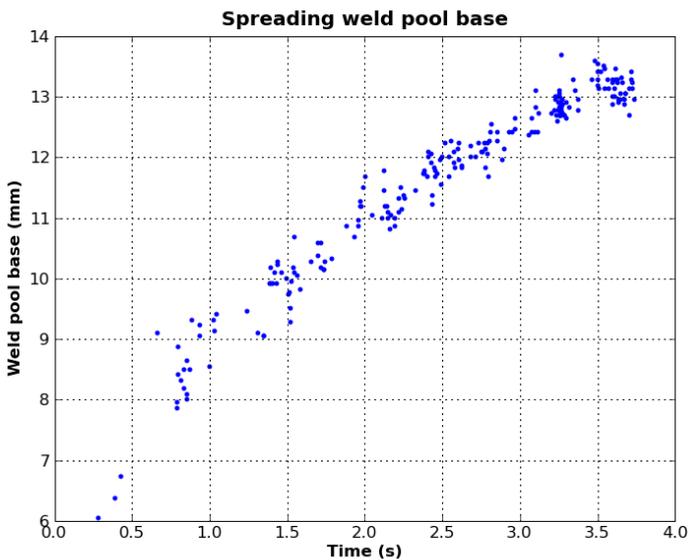


Fig. 6. Spreading base vs time.

In effect, approximately after 1 s of welding, we observe a regular spreading of the deposit base until the extinction of the arc. The weld pool oscillations cause periodic arresting of the average base deposit. After the extinction of arc, there is not variation of base deposit, this phase corresponds to the beginning of solidification. The capillary effect seems thus to be preponderant in front of inertial

effect.

Fig.7 presents the evolution of macrodrop height during welding operation. The observed variation shows nearly the same tendency as base deposit variation.

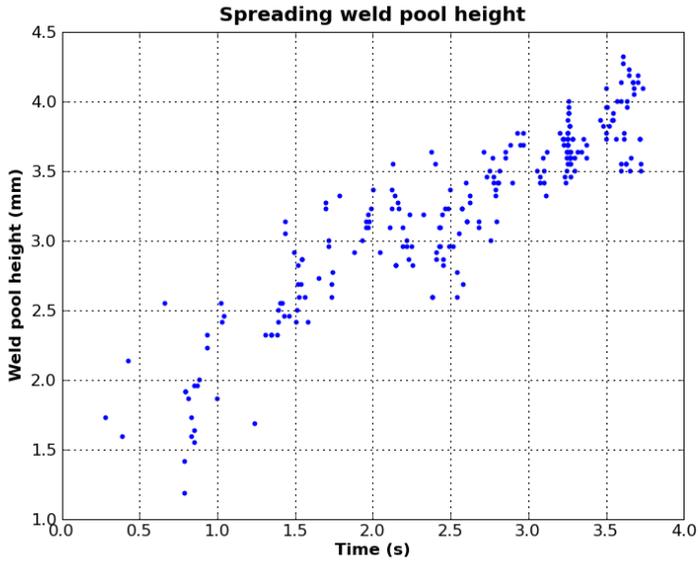


Fig. 7. Spreading height vs time.

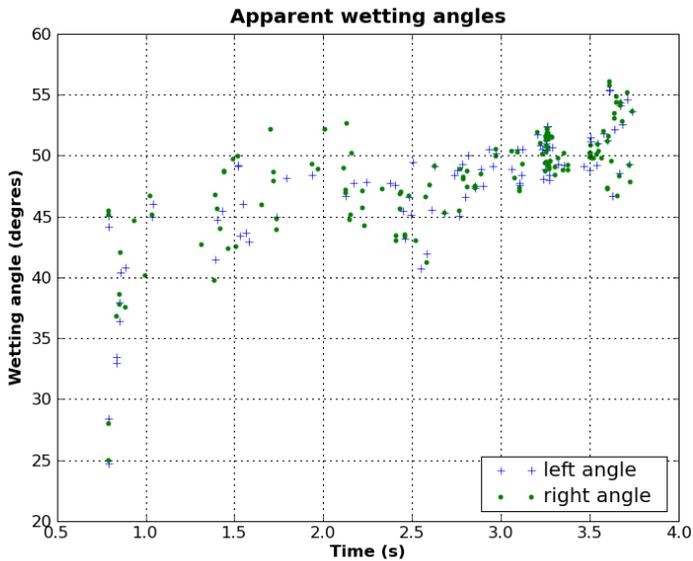


Fig. 8. Apparent wetting angle vs time.

Fig.8 presents the variation of left and right wetting angles as a function of time. The variations are quite the same for both wetting angles according to the symmetric configuration of welding. Once again, we can observe a very quick increase of values of wetting angles for time ≤ 1 s. And then a fluctuation of apparent contact angle about approximately 41° to 53° .

All these measures clearly show the existence of two phases:

1. a first one (for weld time ≤ 1 s) corresponds to the initiation and establishment of the weld pool;
2. a second one (weld time > 1 s) corresponds to regular growth of weld pool with metal deposit.

4 Conclusion

A new experimental device was developed allowing synchronized measurements of different physical parameters during GMA welding (such as optical measurements and process parameters). This study also illustrates the ability of numerical libraries (BAME & erCv) for analyse of acquired datas. The first experimental results showed the possibility to access to characteristics parameters. For example, we observed that the evolution of weld pool during pulsed metal deposition was characterized by the existence of two distinct phases (a dynamic one for early weld times and a more regular one).

Initial results showed the potential of the system for weld analysis and its complementary relation with simulations. Therefore, the experimental study during the arc welding process will be continued for the better understandings of its physical phenomena.

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