Experimental characterization of the weld pool flow in a TIG configuration

M Stadler¹, M Masquère¹, P Freton¹, X Franceries²,³ and JJ Gonzalez¹
¹Université de Toulouse ; UPS, INPT, CNRS ; LAPLACE (Laboratoire Plasma et Conversion d’Energie) ;
118 route de Narbonne, F-31062 Toulouse cedex 9, France.
²INSERM, UMR1037 CRCT, F-31000 Toulouse, France
³Université Toulouse III-Paul Sabatier, UMR1037 CRCT, F-31000 Toulouse, France

E-mail: marine.stadler@laplace.univ-tlse.fr

Abstract. Tungsten Inert Gas (TIG) welding process relies on heat transfer between plasma and work piece leading to a metallic weld pool. Combination of different forces produces movements on the molten pool surface. One of our aims is to determine the velocity on the weld pool surface. This provides a set of data that leads to a deeper comprehension of the flow behavior and allows us to validate numerical models used to study TIG parameters. In this paper, two diagnostic methods developed with high speed imaging for the determination of velocity of an AISI 304L stainless steel molten pool are presented. Application of the two methods to a metallic weld pool under helium with a current intensity of 100 A provides velocity values around 0.70 m/s which are in good agreement with literature works.

1. Introduction

Tungsten inert gas (TIG) welding is widely used in industry. This technique performs an electric arc between a tungsten electrode and a piece of metal. This process involved a shielding gas as argon, helium or mixtures at atmospheric pressure. The heat transfer between the arc and the work piece leads to a metallic weld pool. The molten pool movements may be explained by the combination of four forces [1]: Marangoni [2], Laplace, drag and gravity forces. Weld pool shape is related to the molten zone motion during the process. This flow motion and the surface velocity are influenced by parameters such as arc length [3], shielding gas [4, 5], current or sulfur content of the metal work piece [6, 7]. The depth and shape of the pool are of greatest importance as they determine the thickness and the strength of the weld. It is thus essential to understand the flow behavior to control the weld quality. This understanding involves the characterization of the weld pool surface movement and the associated velocity.

Literature provides several works using modeling to describe either the material [8, 9] or the whole process with the interaction [10, 11]. Anyway, based on our knowledge, there is a lack of experimental works regarding the velocity estimation in a TIG configuration. This issue is treated with particle tracking velocimetry [12] or particle imaging velocimetry [13]. In these works, application of these techniques on a 316L stainless steel anode in interaction with an argon arc provides velocity values of 0.7 and 0.13 m/s. The development of a diagnostic method appears as a necessity as much to
the weld pool phenomena understanding as model validation.

In this work, two diagnostic methods based on high speed imaging and on pixel intensity evolution in a time series of images are presented. The development of these methods and their application to the estimation of velocity on molten pool surface are described. The first method relies on Hlina works [14] and uses phase angle difference coming from Fast Fourier Transform of pixel intensity to estimate velocity whereas the second one consists in tracking bright pixels in time on a selected area of the image. These techniques are introduced in the section 2. Section 3 describes the applications of the two methods on a validation case. In the last section, both methods are applied to an arc transferred configuration and velocity of a stainless steel weld pool under helium is obtained, compared and discussed.

2. Diagnostic methods developed

Until now, weld pool velocity was measured in our work by analyzing the wave front displacement of weld pool oscillations on successive frames extracted from high speed camera acquisitions. This method gave access to a good estimation of velocity values since there were in good agreement with those provided with numerical modeling or with the few experimental works founded in literature. Anyway, this method had the drawback of being really time consuming since it was done manually: video acquisitions own at least 3000 frames. Automation of the method needed to be developed. Nevertheless, it remains a reliable method to us and it is used as a reference value to validate the two diagnostic methods developed and is described below (section 3).

2.1. Method 1: Phase angle difference for velocity estimation

Direct observation during the weld process pointed out wavelet formations on the surface of the molten pool which can be assumed as oscillations. As Hlina reported in its work, the Fast Fourier Transform (FFT) was used to evaluate the gas velocity on a plasma torch thanks to the arc jet oscillations. The optical emission of the plasma jet was detected and recorded with photodiodes along the jet axis leading to the detection of the time shift between two diodes [14]. As sketch in figure 1, the method is based on the measurement of the phase angle difference from two points separated with a distance d along the plasma flow [14]. By the mean of the FFT, a linear dependence between the phase angle difference extracted from two signals (s_1(t) and s_2(t)) and the frequency is assumed. The slope \( \Delta \phi \Delta f \) of the linear arrangement of the phase angle difference allows then to estimate the related velocity through \( v = 2\pi d \Delta f \Delta \phi \) (1), where d is the distance between the two signals extracted from two points of the acquisition, \( \Delta f \) the frequency and \( \Delta \phi \) the phase increment.

![Figure 1: Two time signals extracted from two points separated with a distance d provide phase angle difference \( \Delta \phi(f) \) thanks to FFT](image)

While it was used for gas oscillations in [14], this method has been transposed to molten pool oscillations.
2.2. Method 2: Bright pixel tracking for velocity estimation

Direct observation during the process pointed out displacement of bright pixel on the molten pool surface characteristic of the wavelet movement. The second method uses this pixel intensity evolution with time. As presented in figure 2, a segment [AB] of the image is selected on each frame and a map representing pixel intensity with time is obtained. This map displays maxima of intensity which are typical of the wave front displacement. Line joining several maxima gives access to the wavelet displacement velocity with the ratio $\frac{\Delta \text{pix}}{\Delta t}$.

![Figure 2: A selected area [AB] extracted on each frames gives access to an intensity map as a function of time](image)

3. Validation case: wavelet velocity induced by a water drop

The two methods have been first performed on a simplified case in order to test them. The metallic weld pool movement has been assimilated to oscillations created by successive drops on water surface (figure 3). Velocity value has been deduced with the two methods and compared to the reference value obtained with direct observation of our videos. It allows us to follow the wave front displacement on successive frames. Suitable calibration provides the velocity value with the simple relation $v = \frac{d}{t}$ (2).

In this case, acquisitions have been done with a frame rate of 10 000 fps and a spatial resolution of 100 µm. Direct observation gives access to a velocity value of $0.20 \pm 0.02$ m/s.

![Figure 3: Frame extracted from video acquisition to visualize the water wave front induced by a water drop](image)
3.1 Method 1: Phase angle difference for velocity estimation

Intensity of two signals extracted from high speed camera acquisitions and separated with a distance of 2 pixels has been extracted on the whole recorded frames. FFT provides phase angles of the two signals. Phase angle difference has then been drawn in function of the frequency.

![Figure 4](image)

**Figure 4**: Validation case: phase angle difference as a function of the frequency for two signals separated with a distance of 2 pixels (a) on the theoretical frequency range $\Delta f_{\text{obs}}$ calculated and (b) on a reduced range of frequency.

The ratio $\frac{\Delta \phi}{\Delta f}$ is given by the slope of the linear arrangement of the phase angle difference (drawn on solid line in figure 4(b)). Points displaying between -100 and -360 deg correspond to phase jump when the phase is unwrapped.

Distance $d$ is measured with the image calibration (1 pixel = 100 µm) done before the acquisition. With this ratio, the velocity value is estimated at $0.24 \pm 0.02$ m/s which is in good agreement with velocity estimated with our reference method.

In figure 4 (a), the phase angle difference is observed on a specific range of frequency ($\Delta f_{\text{obs}}$) on which the phase angle is unwrapped. It is strongly linked to the chosen distance between the two signals extracted and the assumed velocity. As the distance rises between the signals, for a given velocity, the observation frequency range decreases. However, phase angle difference often needs to be observed on a frequency range smaller than $\Delta f_{\text{obs}}$ because of the reduction of information in the highest frequencies noticed in the analysis of the frequency spectrum. This is the case in the figure 4(a) where the theoretical calculus gives a observation frequency range from 0 to 1 kHz but where the information is clearer if the range is limited to 600 Hz (figure 4(b)). Furthermore, another parameter seems essential. It has been noticed that for a too high distance between considered pixels, reduction of the observation frequency range seems no longer sufficient. It seems that beyond few pixels, signals are less correlated and it gets more difficult to provide reliable information. Figure 5(a) displays the phase angle difference for two signals extracted with a distance of 6 pixels. Theoretical calculus give a maximal frequency of 333 Hz but it is clearly shown that information is harder to get than the previous case presented in figure 4: here (figure 5(a)), a linear arrangement is supposed on the first hundreds of hertz. If the frequency range is reduced to 100 Hz (figure 5(b)) as explained before, the ratio might be obtained with the slope (solid line displays in the figure) and the velocity deduced is $0.26 \pm 0.02$ m/s. While the obtained value is still close to the attempted one, it seems more careful to choose a smaller distance to get a number of points higher and a linear arrangement more obvious, as presented in figure 4. Moreover, if we look closely to the extracted signal in time, an absence of correlation between them when the distance gets too important appears: figure 5(c) (resp. figure 5(d)) displays...
intensity for two signals (solid line and dash line) separated with a distance of 2 pixels (resp. 6 pixels). It is clearly shown that signals 1 and 2 in figure 5(c) presents the same pattern shifted in time whereas figure 5(d) shows a lack of correlation as mentioned above.

Figure 5: (a),(b) phase angle difference as a function of the frequency for two signals separated with a distance of 6 pixels; pixel intensity as a function of time for two signals separated of (c) 2 pixels and (d) 6 pixels

From this first test we can conclude that the distance and the observation frequency range must be chosen carefully for a good use of the method.

3.2 Method 2: Bright pixel tracking for velocity estimation

Intensity of a section of the image (100 pixels in length) has been extracted on the whole recorded frames and juxtaposed to obtain an intensity map with time. The map related to the water drop case is displayed in figure 6. The ratio $\frac{\Delta \text{pix}}{\Delta t}$ is deduced from the lines (drawn in solid line in the figure)
joining maxima. Distance $d$ is estimated with our image calibration (1 pixel = 100 µm) and number of frames provides time with the frame rate used during acquisition (10 000 fps). The velocity value is estimated at $0.21 \pm 0.02$ m/s which is also in good agreement with velocity estimated with our reference method.

**Figure 6**: Intensity map as a function of frames related to the water drop case and line (solid line) joining maxima used to velocity estimation

4. **Results and discussion**

The two methods have then been performed on metallic weld pool obtained with the process described below.

An arc transferred configuration which is close to a TIG configuration is available in our team (figure 7). The electric arc is created between a thoriated tungsten cathode with a tip angle of 60° and a cylindrical anode (5 mm in height and 50 mm in diameter) of 304L stainless steel considered as the work piece. The length of the arc is adjustable but set at 5 mm for this experiment. Time of interaction is limited to 2 minutes. The device is placed in a hermetic and water cooled reactor within the gas is injected. The inert atmosphere is assured by helium with a flow rate of 10 Nl/min. Current intensity is set at 100 A. The measurements are performed with a high-speed camera set at 15 000 frames per second with a spatial resolution of 46 µm. This rate is chosen to be high enough to see the weld pool movements and to get a suitable resolution to observe the entire weld pool.

**Figure 7**: Experimental set up used (left) and frame extracted from video acquisition of a stainless steel weld pool under helium (right)
Figure 8 presents results obtained with the two methods. Application of method 1 (figure 8(a),(b)) displays the linear arrangement of the phase angle difference from two signals extracted with a distance of 2 pixels. As presented in figure 8(a), the observation frequency range is reduced to 2500 Hz (figure 8(b)). The velocity values obtained is $0.74 \pm 0.02$ m/s. Application of method 2 provides an intensity map as a function of frames (Figure 8(c)). The ratio $\frac{\Delta \text{pix}}{\Delta t}$ is measured from the solid lines drawn in figure 8(d). Only frames from 1300 to 1600 are presented here to ease the observation but the ratio has been calculated on the entire map. Velocity estimated with the application of method 2 is $0.71 \pm 0.02$ m/s. Reference velocity given by direct observation is $0.70 \pm 0.02$ m/s.

![Figure 8: Applications of (a)(b) method 1 and (c)(d) method 2 to a metallic weld pool under helium with a current intensity of 100 A](image)

This first test shows a good agreement between the two methods and our reference velocity value. Modelling of the interaction of a 5 mm arc and a 304L stainless steel anode under helium with an intensity current set as 150 A allow to estimate a velocity on the surface of the weld pool of 0.59 m/s after 20 second of interaction [15]. Tanaka et al.[16] pointed out in their work that velocity values changed in time and with the content in sulfur of the material, so we remain careful since to our knowledge, any literature work provides velocity values with the exact same conditions as ours (intensity, time after interaction).
5. Conclusion
This work is a first step in velocity estimation in weld pool. Two diagnostic methods based on high speed imaging have been presented here and validated on a simple case. First results on a weld pool configuration have then been displayed. Results seem encouraging. Nevertheless, these methods need to be improved and results obtained need to be compared: further experiments will be carried out with operational conditions closer to those found in literature. Once these results compared, this work will lead to further investigations: influence on current intensity, nature of the shielding gas and nature of anode material on velocity in weld pool.

6. References
[1] Tanaka M et al 2002 Metall. Mater. Trans. A. 33A 2043
[2] Mills KC et al 1998 Philos. Trans. R. Soc. London, Ser. A 356 911
[3] Ushio M et al 2004 IEEE Trans. Pl. Sc 32 108
[4] Mougenot J et al 2013 J.Phys. D : Appl. Phys. 46 495203
[5] Tanaka M et al 2007 Sci. Technol. Weld. Joi. 12 2
[6] Mills KC and Keene BJ 1990 Int. Mater. Rev. 35 185
[7] Shirali AA and Mills KC 1993 Weld. J. 71 347s
[8] Kim WH et al 1997 Numer. Heat Transfer Part A 32 633
[9] Dong W et al 2011 Int. J. Heat Mass Transfer 54 1420
[10] Lu F et al 2006 Comp. Mater. Sci. 35 458
[11] Mougenot J et al 2013 J.Phys. D: Appl. Phys. 46 135206
[12] Henrikson P 2005 Math. Mod. Weld Ph. 7 125
[13] Zhao CX et al 2009 The 8th International Conference Trends in Welding Research (Pine Mountain, ASM international)
[14] Hlina J et al. 1996 Acta Tech. CSAV 41 373
[15] Murphy AB et al. 2009 J. Phys. D : Appl. Phys 42 194006
[16] Tanaka M and Lowke JJ 2007 J. Phys. D : Appl. Phys. 40 R1