Application of Time-Frequency Methods for Assessment of Gas Metal Arc Welding Condition

Jacek Górka and Wojciech Jamrozik

Abstract Gas Metal Arc Welding (GMAW) is a popular method of material joining, widely used for a variety of critical industrial structures. Assuring high quality of joints is than a vital task. Welding is a highly dynamic and non-linear process, thus an application of time-domain or frequency-domain methods is often not suitable for evaluation of welded joints quality. To fully describe the correspondence between the geometry of welding arc, parameters that express the quality of joint, and the welding arc current, being the most important steerable parameter of a GMAW, time-frequency methods (TFM) of signal analysis should be applied. In the paper application of ensemble of STFT and EMD (Empirical Mode Decomposition)-based estimators to evaluate the stability of a GMAW process, that results in the quality of joint. Proposed method of feature extraction was applied on the real data taken during several GMAW realizations with different conditions (changes in welding current, arc voltage, shield gas flow, wire feed speed, etc.). In the active experiment process parameters were acquired. Performed investigations revealed that in comparison to traditional as well as separately used TFM, ensemble of TF estimators gave better performance in a GMAW condition assessment.

Keywords Welding · Time-frequency transform · Condition assessment

1 Introduction

Gas Metal Arc Welding (GMAW) is a technique commonly used for joining metal materials. It is a dynamic and non-linear process. The quality of seam and created joint is closely related to features of welding arc as well as droplet transfer mode. To obtain a desired mechanical and metallurgical properties of joint, several parameters,

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J. Górka · W. Jamrozik (✉)
Silesian University of Technology, ul. Konarskiego 18a, 44-100 Gliwice, Poland
e-mail: wojciech.jamrozik@polsl.pl

J. Górka
e-mail: jacek.gorka@polsl.pl

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especially electrical ones, are monitored and controlled. Monitoring of joint quality is a vital issue, especially in those branches of industry, where defective welds lead to losses in production and necessitate expensive repair [1]. Electrical signals describing the welding arc behaviour are typically non-linear and non-stationary. Because of those signal properties common signal processing and analysis methods, that can be executed in only time domain or frequency domain, are not suitable for assessment and evaluation of welding process stability and joint quality. Point estimators and classifier ensembles were used to identify inconsistencies appeared in GMAW [2]. Also autocorrelation peak coefficient of various welding parameters was used to describe process stability [3]. Modern and complex time-frequency analysis methods have been applied to assess condition of welding process and quality of joints. Most popular methods are Short Time Fourier transform (STFT) and Wigner-Ville distribution (WVD). Both of them were used to establish a correspondence between TF spectrum and process stability [4, 5]. To overcome main disadvantage of STFT, namely constant resolution for all frequencies, wavelets were introduced. This type of transformation was applied to determine seam geometrical parameters, penetration depth and process stability [6]. Recently Hilbert-Huang transform has been applied to arc stability evaluation in short-circuiting GMAW. There was found, that the welding was more stable when the time frequency entropy calculated for Hilbert-Huang transform of welding current signals, was larger [7]. Although many signal processing methods were successfully applied, there is no approach, that utilize extracted features fully to assess welding process and welded joints.

1.1 Time-Frequency Representation of Signals

Short Time Fourier Transform is an iterative procedure, consisted in applying Fourier Transform for a part of signal catted by window of certain length. Window is moved by time index until end of processed signal is reached. Formally STFT is given by following equation:

$$F_x(t, \nu; h) \int_{-\infty}^{+\infty} x(u)h^*(u-t)e^{-j2\pi\nu u}\mathrm{d}u \tag{1}$$

where $h(t)$ is a short time analysis window localized around $t = 0$ and $\nu = 0$. Main drawback of STFT is limited precision, given by size of window. Having high resolution in time domain, resolution in frequency domain will be relatively low. Moreover STFT gives same resolution for all frequencies, while sometimes it is valuable to have more flexible approach [8].

Wigner-Ville distribution (WVD) is a spectrum corresponding to each time based on this time as the centre, which conducts the Fourier transform to the results from the signal multiplied by the right and left of all parts [9]. The advantage of the WVD is the good resolution in both domain, namely time and frequency. The oscillation characteristics of the cross-terms can be reduced by the smoothing of WVD, that is, a

Fig. 1 Test stand with the computer station and the welding device

smooth window function is added in time domain, and then the Pseudo Wigner-Ville distribution (PW) is obtained for a discrete-time signal x:

$$PW_x(t,\nu) = \int_{-\infty}^{+\infty} h(\tau)x\left(t+\frac{\tau}{2}\right)x^*\left(t-\frac{\tau}{2}\right)e^{-j2\pi\nu\tau}\mathrm{d}\tau \tag{2}$$

Empirical Mode Decomposition, EMD, decomposes the signal of interest into oscillatory functions intrinsic to the original signal, defined as Intrinsic Mode Functions (IMFs) [10].

The result of this procedure is a series of IMFs, plus a final residual, r(t). In its core form it was not done much to modify IMF extraction procedure. Modifications come in how some of the steps are carried out, including the maxima/minima detection, envelope formation (interpolation), the way a IMF is identified (i.e. stopping criteria) and how one stops the sifting process. Although EMD is a promising method is also several drawbacks. Most important of them are that the IMFs are not strictly orthogonal each other, mode mixing sometimes occurs between IMFs. The most important issue of EMD is that IMFs cannot be directly interpreted, in other words they don't have straight physical interpretation [11].

It can be noticed, that each of TFR methods has some advantages and disadvantages as well. According to that, it cannot be stated, which of those methods is most universal and generally best one for widest field of applications.

2 Case Study

Current and voltage signals were taken during welding of plates made of steel S235JR (EN 10027-1) with dimensions 300 × 150 × 5 mm on the mechanised welding stand for rectilinear GAMW welding equipped in welding machine Castolin TotalArc 5000

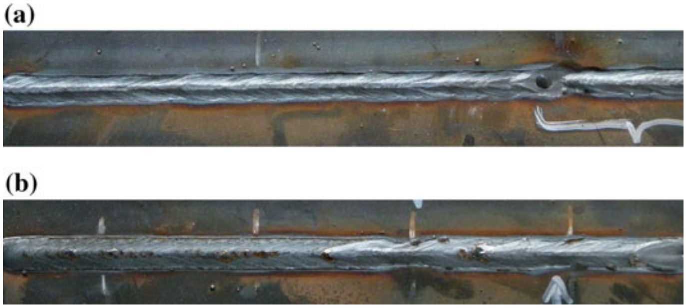

Fig. 2 Exemplary joint made with **a** corroded wire (S4), **b** contaminated with oil (S6)

Table 1 Nominal GMAW parameters

Welding current [A]	Arc voltage [V]	Welding speed [cm/min]	Wire feeding rate [m/min]	Shield gas flow [l/min]	Electrode outlet [mm]
240	25	32	7.4	15	15

(see Fig. 1). The edges of the joined plates were bevelled at an angle of 60° and the offset between them was b = 1.0 mm. For joining a solid electrode wire with a diameter of 0.2 mm (Castolin CastoMag 45255) and a shield gas M21 (82%Ar+18%CO_2) were used. Nominal welding parameters are presented in Table 1. It was checked, that those parameters lead to correct joint made in a stable process.

Series of experiments simulating different faults of welding process were carried out. It permitted to record the collection of sequences of infrared and vision images for 12 different states of welding process classified in the following way: S1 - Correct welding process. S2 - Welding with decay of the shielding gas flow. S3 - Welding of the plates with distinct outbreaks of atmospheric corrosion on the welded surfaces. S4 - Welding with use of corroded wire. S5 - Welding of plates with irregularities of the plate edges from side of the weld root. S6 - Welding of plates with oil contamination. S7 - Welding with deviation of current. S8 - Welding of plates with different offset intervals. S9 - Welding with deviation of voltage. S10 - Welding of the plates with improper welding groove geometry. S11 - Welding with deviation of speed. S12 - Welding with use of worn rollers of wire feeder (see Fig. 2).

Welding current and arc voltage were measured during welding with frequency of 25 kHz. Then signals were down sampled and down pass filtered. Exemplary current signals were presented in Fig. 3.

2.1 TFR of Welding Signals

To generate features, that can be used for assessment of welding process stability and secondly the quality of welded joint, several TFR of acquired electrical signals

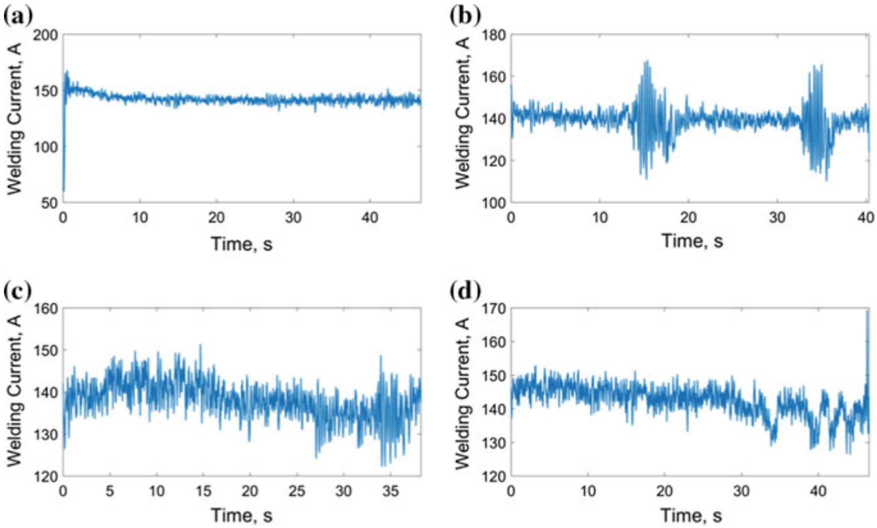

Fig. 3 Exemplary time signals for conditions: **a** S1- correct process, **b** S2 lack of shield gas, **c** S9 change of voltage, **d** S11 wrong groove geometry

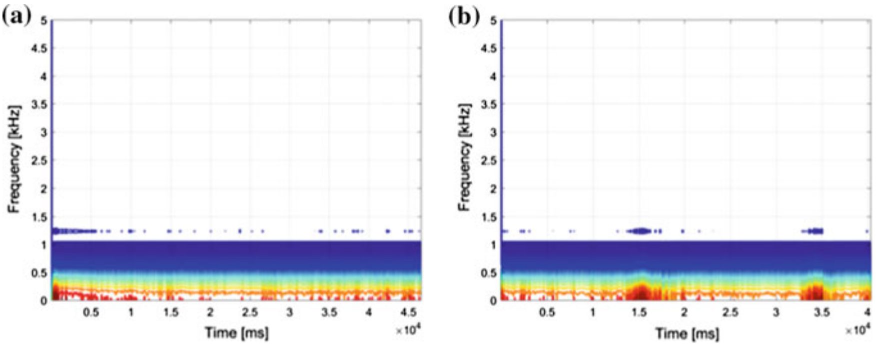

Fig. 4 STFT representation of welding current: **a** S1 condition correct process, **b** S2 condition lack of shielding gas

were calculated. First STFT of signal was calculated. The number of FFT points was 512 and the Hamming window of length 21 points was used. Exemplary results can be seen in Fig. 4. Comparing results it is clearly visible, that for lack of shield gas, that frequency components of higher amplitude appeared in time, when the gas flow was disturbed.

Applying to current signal PW distribution, result are similar to those obtained by STFT. Nevertheless, having better resolution, all frequency components are better distinguishable (Fig. 5).

To obtain more accurate results EMD was applied. It can give interesting information based on the local characteristic time scale of the signal. It can be seen, that

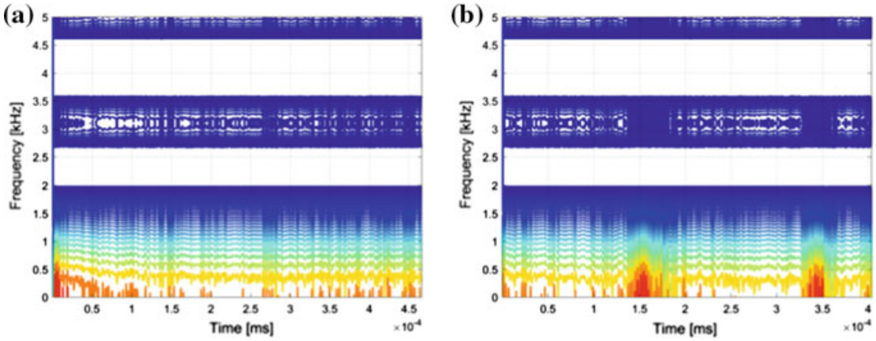

Fig. 5 Pseudo Wigner-Ville representation of welding current: **a** S1 condition correct process, **b** S2 condition lack of shielding gas

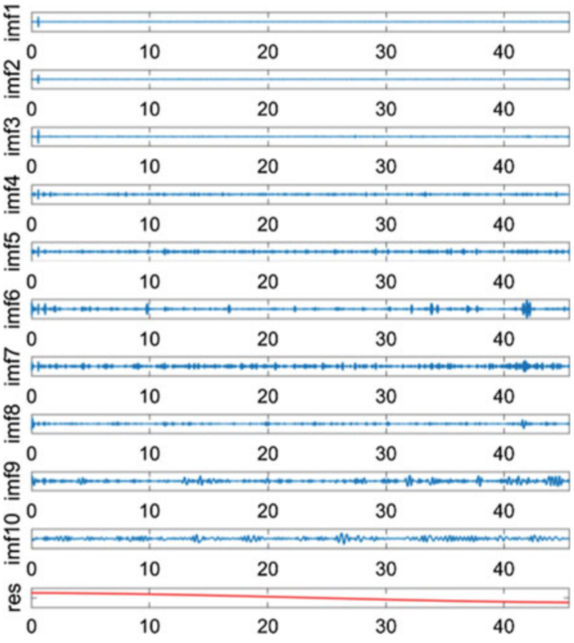

Fig. 6 First 10 IMFs and the rest of the welding current: **a** S1 condition - correct process, **b** S2 condition - lack of the shielding gas

for stable, correct process IMF9 and IMF 10 of welding current signals, are low amplitude noise like signals and there are no visible disturbances, that can be result of the stability of the process (see Fig. 6). When the process disturbance appears, as in the case of decaying od shield gas flow, there are clear variation visible in IMF9 and IMF10 (see Fig. 7). Locations of those variations in time allows to indicate the position of welding instabilities results on the weld surface.

To quantify IMFs first the STFT of each mode was calculated. Spectrogram of the IMF10 of the current signal taken for correct process presents uniform distribution of frequency bands. Increased amplitudes in some time moments cannot be treated

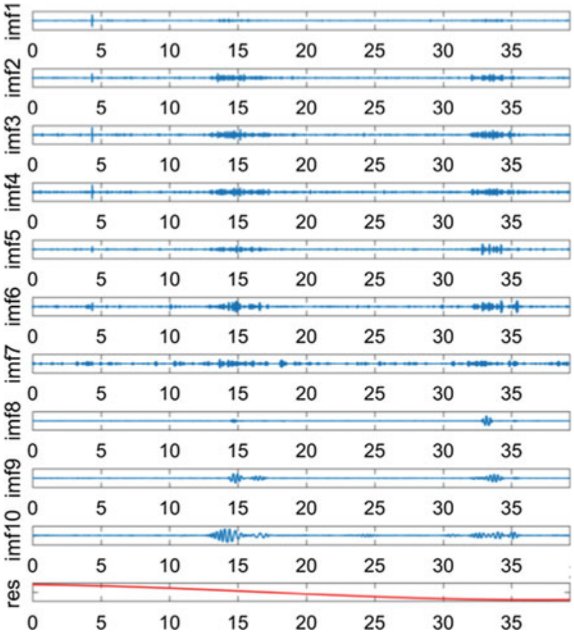

Fig. 7 First 10 IMFs and the rest of the welding current: **a** S1 condition correct process, **b** S2 condition - lack of the shielding gas

as symptoms of potential instabilities leading to joint inconsistencies. Spectrogram of IMF10 calculated for condition S2 point on presence of two time intervals, where process was disturbed (Fig. 8). Positioning of those regions is consistent with the time moment when flow of gas was present. Additionally there is no other signal processing technique needed, because application of thresholding, that was applied to cut out components with low amplitude was sufficient.

2.2 Detection of Welding Instabilities

In order to determine the condition of welding process, classification procedure was developed. For generated TFRs of GMAW electric signals, point features were used, to assess each process. RMS and entropy were used to assess signal in band of about 500Hz for STFT calculated for acquired signals and 200 Hz for IMFs. To validate usefulness of particular TFR method STSF spectrograms were used, as well as spectrograms generated for 9th, 10th and 11th IMFs. Classification was performed by simple K-Nearest Neighbours classifier, where number of neighbours was three, and Euclidean distance was used. Classifiers were validated k-using fold cross validation, for k = 10. The classification was made for detection case, thus there was no

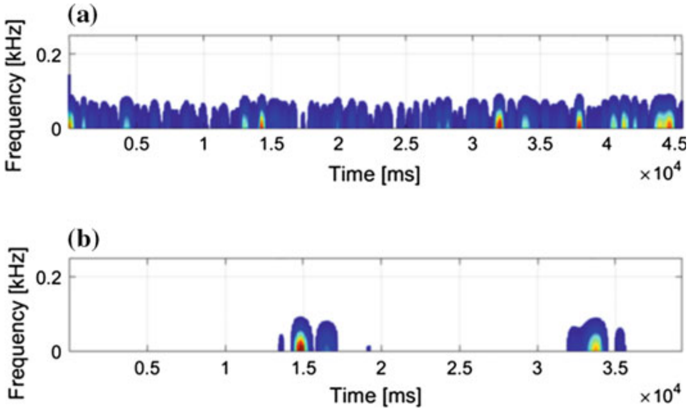

Fig. 8 STFT of the IMF10 for condition S1 (**a**) and S2 (**b**)

Table 2 Nominal GMAW parameters

Classifiers	Signal STFT RMS	Signal STFT Entropy	IMF9 STFT RMS	IMF10 STFT RMS	IMF11 STFT RMS	IMF9 STFT Entropy	IMF10 STFT Entropy	IMF11 STFT Entropy
1	0.0125	0.2	0.0625	0.025	0	0.05	0.2	0.075
5	0.0125	0.0125	0.0375	0	0	0.025	0	0

Table 3 Nominal GMAW parameters

Classifiers	IMF9-IMF11 STFT RMS	IMF9-IMF11 STFT Entropy	IMF9-IMF11 STFT RMS+Entropy
1	0.0125	0.3125	0.1125
5	0.0125	0.0625	0

differentiation between appeared inconsistencies. To increase classification accuracy bagging procedure was used, where there were maximal five classifier in ensemble Training samples for faulty condition were consisted of samples representing states form S2 to S12. Obtained classification errors are gathered in Tables 2 and 3. When single features were taken for classification, best one was the RMS calculated for the spectrogram of IMF11. Simple ensemble building technique, like bagging, increased the classification performance significantly. In the ensemble of classifiers, features calculated from IMF spectrograms were generally better than those calculated from current or voltage signals. Nevertheless detection results are satisfying. To reduce uncertainty of results, that can be connected connected with the selection of feature, classification in multidimensional feature space was performed. It was revealed that the use of all IMF features lead always to best classification accuracy. Nevertheless, there were no studies performed how different feature mixtures will affect classification results.

3 Conclusions

In the paper application of point features calculated for various Time-Frequency Representations of electric signals recorded during welding to detection of possible welding inconsistencies. It was found that spectrograms calculated for IMFs being result of empirical mode decomposition, can be a good basis for feature extraction. Those features have potential to be valuable diagnostic signals. Quantification of detection ability on the basis of extracted features was made using pattern recognition method. Classification has been performed using single classifiers, as well as classifier ensembles. It was found that features calculated for IMFs are best symptoms, having high ability to distinguish correct and incorrect joints. Presented results are preliminary. Further studies will cover application of Hilbert-Hunag Transform and more sophisticated features to quantify realizations of GMAW. Additionally method, that will allow detection of inconsistencies or process instabilities not only for whole process realization but also with indication of time point where disturbance occur.

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