



Research Article

Assessment of arc stability features for selected gas metal arc welding conditions

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Abstract

Stability is a key indicator of the efficiency of the gas metal arc welding operation, and it is linked to other quality indicators like spattering and weld formation. This study describes methods of assessing arc stability for selected gas metal arc welding (GMAW) conditions. It focuses on stability characterization and defines the relationship between process stability and influencing factors. Welding tests were performed using two selected transfer modes the spray and the pulse transfer modes to characterize stability and develop processes further for better overall performance. This scope of parameters was selected to simulate certain range of stability behavior, so it was possible to analyze the factors correlated to stability, their relevance in influencing stability, and consequently to define a calculation algorithm for the determination of stability. Also, stability was calculated and scored based on two scoring indices. With a higher voltage, disturbance levels were noticed to reduce as in the case of 29 V, 31.5 V, and 32.5 V with 32.5 V showing better stability to spattering, smoothness, repeatability, and regularity of the process. Actual values of positive and negative voltage peaks, voltage amplitudes, and their average values and standard deviations in selected analyzed time showed to be relevant indicators to characterize stability of the process. Variations of indicated voltage signals related to explosions showed to have complex patterns in terms of their waveforms. So, all these were analyzed step by step and consequently selected for characterization in the welding conditions that were selected in the scope of this study.

Keywords Spray transfer mode · Pulse transfer mode · S355J2 · Inductance control · Linear waveform · Exponential waveform

1 Introduction

Gas metal arc welding (GMAW) which is also known as Metal inert gas welding (MIG), or Metal active gas welding (MAG) is an arc welding process which allows one to weld ferrous and non-ferrous components. This welding process has been around for over 60 years and has found its application in welding steel, stainless steel, aluminum alloys, etc. In the GMAW process, a wire electrode is continuously fed through an electrode gun and an arc is generated

between the electrode and the workpiece [1, 2]. The heat generated from this arc is used to melt the electrode and the workpiece. This arc is protected with a continuous flow of either an inert gas or an active gas. When compared GMAW to other arc welding processes, it has many benefits which include comparatively high welding speed, higher overall weld efficiency, absence of slags on the workpiece, and ability to weld a wide range of materials with various thicknesses [3, 4], GMAW can be properly applied to assemble components requiring high load capacity [5–7].

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GMAW is also cost-effective and for this reason, it is one of the most commonly used welding processes in the welding industry for manufacturing high-quality welds. However, when producing high-quality welds with little spatter loss, the arc stability of the welding process is still one major concern [8, 9]. Stability is a key indicator of the efficiency of the GMAW operation, and it is linked to other quality indicators like spattering and weld formation quality. There is currently no well-known formulation of the concept of welding process stability. Every researcher studying the stability process understands the process in a different way and applies different indicators of stability [10]. Arc stability means that there will not be a variation in the arc length and there will be a constant/consistent contact tip-to-workpiece distance (CTWD). In order to have a stable arc at least these two conditions need to be met: a) The wire feed speed must be equal to the wire burn rate, and b) The molten metal from the wire must be transmitted to the weld pool with as little disruption to the operation as possible [11, 12]. The burn rate and the feed rate are two entities which play a very important role in GMAW. The burn rate refers to how quickly the filler metal is consumed by the welding arc's thermal energy, while the feed rate refers to how quickly the wire filler metal is fed into the weld [13].

Because the GMAW process is widely utilized in industrial manufacturing, much care is taken to pick the best technique to assure the greatest quality. As a welding process, GMAW has a high level of output, dependability, and automation capability. It permits welding in practically all locations and with virtually all metal alloys with the proper parameter setup.

A complete analysis and evaluation of past research work were conducted to get a comprehensive knowledge of the principle, effects, and operation of GMAW, providing a picture of the present state of the art in this field of study.

Arc stability and metal transfer that are affected by arc length, shielding gas oxidizing potential and power supply Voltage (V)/Current (I) characteristic was studied [11, 14]. The experimental phase was carried out employing two static power source characteristics, namely constant current, and constant voltage. During the transition from unstable repulsive globular metal transfer to stable spray transfer operation, strong fluctuations in arc length and current level were observed with a constant voltage characteristics power source, whereas no substantial disparity in arc length was noticed with a constant current characteristics power source. Rather a distinct change in metal transfer and arc appearance was noticed when the arc length was changed. The experimental results showed that when the welding current and the helium shielding gas concentration increased, the voltage differences between the transfer modes decreased.

Based on results obtained from time variation of welding voltage and current using different shielding atmospheres, Marjan Suban et al. [15] investigated methods of determining arc stability. The experimental process focused on measurements of welding current and voltage with a fully automated MIG/MAG welding process. From the experimental results obtained, it showed that stability analysis using cyclogrammes is very fast although it is very complicated to use. It was also concluded that the short circuit transfer is more stable when pure CO₂ is used as the shielding gas. On the other hand, when welding with the spray transfer, a four-component mixture of 65% Ar/26.5% He/8% CO₂/0.5% O₂ produced a more stable arc.

The indicators of stability of the GMAW process were investigated by Lankin [10]. These indicators were chosen based on the welding method and mode of metal transfer from the electrode to the weld pool. It was concluded that the welding consumables, welding parameters, and equipment have a key role to play in the stability of the welding process.

Several researchers have studied the use of arcs in industrial welding and provided an overview of the arc phenomena. They discussed the arc characteristics, welding arcs classification, benefits, and weaknesses. It was concluded in the study that when welding with the short circuit transfer, a low deposition rate is observed with a risk of lack of fusion due to the low heat input. The spray transfer arc is limited to welding in the flat and horizontal position while the globular transfer is not so popular and is usually accompanied by a large amount of spatter [16–18].

Droplet sizes produced in GMAW with the use of the static balance theory were investigated by Uddin et al. [19]. Also, the pinch instability theory was investigated with the results compared to the measurements obtained from the experimental procedure. The metal transfer was observed using a high-speed video camera which showed the gradual droplet detachments during the transfer. From the experimental results, it was revealed that changes in the shielding gas or electrode extension effect on the metal transfer mode were not explained by the pinch effect instability concept. It was also concluded that it is necessary to analyze other forces which act as repelling forces when the globular spray transfer is being assessed.

Arc behavior, melting rate, and droplet detachment were investigated by Harwig et al. [20] using a high-speed camera for variable polarity GMAW. The influence of variable polarity GMAW waveform on melting rate was investigated using constant arc-length, CTWD, and deposit area experiments. The power source used for this experiment was the OTC AC/MIG 200 power supply. The findings of the experiments revealed that the melting rate was highly dependent on the current waveform, polarity, droplet size,

and metal transfer events that happened during each waveform phase.

Metal transfer in solid wire GMAW was studied by Scotti et al., and Zhang et al. [21, 22]. Several tests were carried out using various combinations of gas-wire parameters with metal transfer observed and characterized using a laser shadowgraph system and high-speed filming. A metal transfer categorization was proposed, with modes that are independent of the type of shielding gas or welding power source.

New observations in arc stability in anti-phase synergic pulsed GMAW were investigated by Quadir et al., and Moynuddin and Sharma [8, 23]. It was revealed that, unlike the traditional GMAW method, which is thought to produce instability, excess spatter, and so on, welding with dissimilar current may generate welding arc stability, which has a significant impact on microstructure, heat affected zone (HAZ), hardness, and so on.

The use of synchronized welding signals with a high-speed camera to investigate the behavior of voltage signals in pulsed GMAW processes with various drop transfer mechanisms was demonstrated by Praveen et al. [24]. The welding arc has a significant impact on droplet detachment, according to the findings. Voltage oscillations during droplet detachment can also be utilized to characterize the process behavior, according to the study.

Cold wire GMAW in direct current electrode positive welding and direct current electrode negative welding was compared by Assunção et al. [25]. Results revealed that with direct current electrode negative (DCEN) arc climb can be suppressed which in turn improves the stability. DCEN has also higher penetration, HAZ, and dilution when compared to DCEN.

The contrasting features of high-performance MIG/MAG penetration were studied by Dutra et al. [26]. It illustrated that if certain conditions such as the power source are met voltage control can produce good results. What matters when choosing gas is its appropriateness in relation to the energy source, since this must offer adequate dynamic responses in order for the molten pool's metastable equilibrium to be maintained.

Y. Li [27] investigated defect detection on weld bead profiles using a light-based vision detection system. Results from the experiments showed that with the use of a vision-based system, weld bead dimensions can be successfully monitored and measured.

Reflected laser lines which are segmented, and detected were investigated by Wang [28]. Innovative image processing techniques were also proposed to accomplish this goal.

The effect of shielding gas in optimizing the GMAW process was studied by Mvola and Kah [29]. It discussed the shielding gas properties and effects of different gas

mixtures and control. It was concluded that pure gas functions admirably but shielding gas combinations provide the best results.

A high-speed video laser-based shadow graphing system was used by Rhee and Kannatey-Asibu [30] to examine metal transfer for various transfer modes. The transition current rose when the carbon dioxide to argon ratio was raised, according to the findings of the experiments. It was also discovered that a higher carbon dioxide concentration enhanced the rate of spattering.

This study aims to define GMAW stability control parameters for selected weld metal transfer modes (spray and pulse) alongside determining the relationship between process stability and welding performance. By doing this it will be possible to identify which factors are correlated with stability and also the patterns and parameters that best suit selected transfer modes for specified applications.

The study has considered many factors in assessing arc stability, and has attempted to answer the following questions: what is the optimal way of characterizing stability in selected metal transfer modes? which factors are mostly correlated to stability and could be analyzed and evaluated using image and data processing? how do voltage, current, and wire feed influence process disturbances, and deviations?. To respond to these questions, in the next section, the data collection methods, data processing and acquisition setup, and welding power source will be described; then, a comparison of the different welding transfer modes mentioned above for the analysis of the stability of the welding process based on the measurements of the welding current and welding voltage will be performed, and finally in the last section, the results of the signal processing and their comparison will be interpreted in terms of the stability of the welding process.

2 Materials and methods

To collect data, quantitative research in the form of experiments were performed to give answers to the research questions. The experiments were performed by welding on carbon steel (bead on plate) using different welding transfer modes (spray and pulse) at varying welding parameters to characterize stability. These experiments were performed in order to create a basis for the analysis and comparison of various welding parameters such as the voltage and inductance control rate. Certain stability behavior scope of the process was simulated by varying voltage and inductance control in order to have the possibility of analyzing various factors related to stability and determination of the ones having relevant influence. The experiment was carried out in two phases. First was welding using the spray

transfer mode at three different welding voltages and inductance values. Voltage disturbances were analyzed and as well as explosion levels from image data. The second phase was welding with pulse comparing two different types of waveforms. The experiments were carried out at ESAB R&D, and the measurements were performed using image data from a high-speed camera and data from HKS weld analyst. Some of the equipment used for this experiment include an ESAB welding robot consisting of the wire feed unit and DC power source, which was used to perform the weld, a high-speed camera which was used to record the weld metal droplet detachment, a high-power laser which was used to improve the image quality obtained from the high-speed camera, etc. The quantitative findings of the experiments and analyses were then statistically evaluated by analysis of variance and statistical error percentage calculated. The results from these experiments were analyzed using both image analysis from a highspeed camera and data acquisition from HKS weld analyst with measurements carried out post-weld from image data. These methods are illustrated in Fig. 1.

2.1 Experimental work

The experiments in this study aimed to assess the arc stability of a GMAW process using two different transfer modes: the spray and the pulse transfer modes. Optimal parameters were selected and developed during the experimental phase based on the response of the process in conjunction with its stability disturbance aspects. Welding Equipment, consumables, and power source.

2.1.1 Welding power source

The welding power source used is called Aristo 500ix ESAB welding power source. It has a robust feed unit and control U82. This power source is a three-phase DC power supply which can operate in both constant voltage (CV) and constant current (CC) operating modes. The Aristo 500ix is a portable heavy industrial pulse power source with a mechanical design that is both durable and dependable. It is an ideal choice for pulse applications when combined with Robust Feed U6. With its advanced pulse functionality composed of up to 250 pre-programmed synergic lines, it can reduce heat input and spatter. It is also composed of an IP23 rating which can be used indoors and outdoor. Table 1 shows some of the specifications of the Aristo 500ix.

For the GMAW process, the constant voltage operating mode is generally used and for this research work, it was also employed.

2.1.2 Data processing and acquisition setup

This setup consists of the HS camera Photron FASTCAM Nova S12, frame rate of 10kfps, shutter speed 0,7 μ s, and a resolution of 1024 X 1024 was used for analyses. A laser unit (500 W + 10%) of wavelength $806 \pm 10\%$. Also connected to this setup is the HKS weld analyst for data acquisition. It is used to analyze voltage, current, and wire feed speed (WFS) signals. The HKS weld analyst has a sampling rate of 23 kHz with HKS sensor P1000-S3 1000A/100 V. The data and image processing setup (Fig. 2) were used to observe the weld metal transfer. Data analysis was also performed by observing electrical signals using the HKS data analysis software. A schematic of the HKS setup is illustrated in Fig. 3.

Fig. 1 Flow chart showing an experimental method

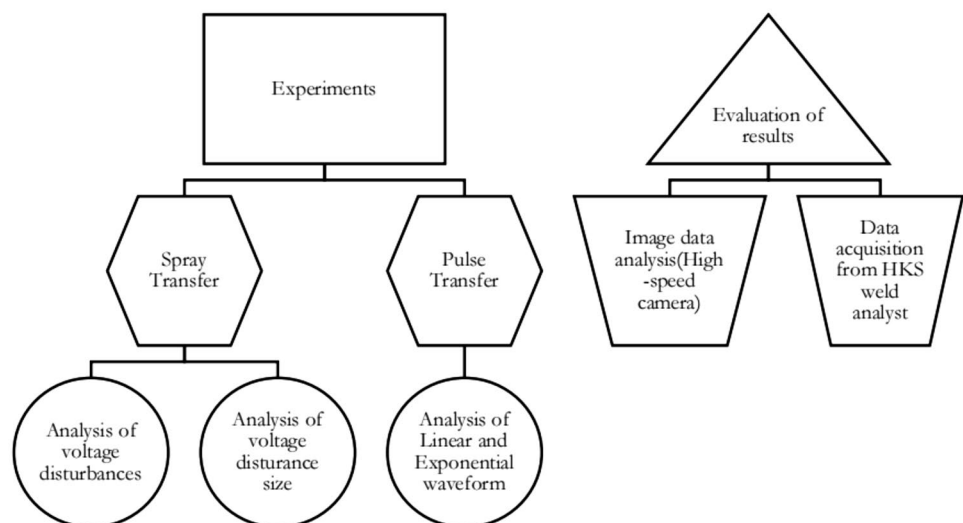


Table 1 Welding power source specifications

<i>Specifications</i>	
Main Voltage	380–460 V \pm 10%, 3ph, 50/60 Hz
Welding output GMAW(MIG/MAG)	500 A / 39.0 V at 60% Duty cycle 400 A / 34.0 V at 100% Duty cycle
Welding output SMAW(Stick)	500 A / 40.0 V at 60% Duty cycle 400 A / 36.0 V at 100% Duty Cycle
Welding output GTAW(TIG)	500 A / 30.0 V at 60% Duty cycle 400 A / 26.0 V at 100% Duty cycle
Setting range GMAW(MIG/MAG)	16 A / 14.8 V -500 A / 39 V
Setting range SMAW (MMA)	16 A / 20.6 V -500 A / 40 V
Setting range GTAW (TIG)	5 A / 10.2 V -500 A / 30 V
Open circuit voltage	58 V
Efficiency at max current	88%
Power factor at max current	0.91
Dimensions L×W×H	712×325×470 mm
Weight	58,5 kg
Operating temperature	– 20 to + 40 °C
Enclosure class	IP23
Application class	S
Insulation class	H
Certification Mark (Standards)	CE
<i>Cool 2 Cooling Unit</i>	
Supply voltage	40 VAC
Cooling power	1 kW
Coolant volume	4,5 l
Max flow	1,8 l/min
Max pressure	4.6 bar
Dimensions L×W×H	680×330×230 mm
Weight	15 kg

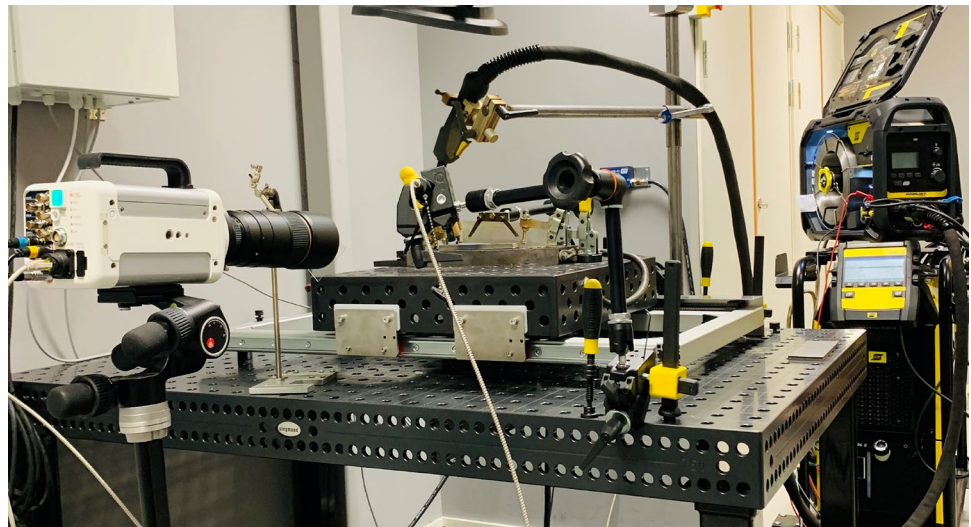
Fig. 2 Image and data processing setup

Figure 2. shows a picture of the image data and processing set used in performing the experiments. Show in this setup is the high-speed camera, power source,

wire feed unit, welding torch, and adjustable workpiece holder.

A schematic set of the HKS weld analyst used for data acquisition of electrical signals showing connections to the camera, computer, and laser unit is shown in Fig. 3.

2.1.3 Base material

This experiment was performed on carbon steel with EN10025-2 classification S355J2 with dimensions 10 × 50.4 × 164 mm. The material composition and mechanical properties are shown in Table 2. The material was chosen because of its wide range of applications. The surface condition of the base material was a sand-blasted surface. This material is the most widely used in manufacturing for a variety of engineering purposes, including automobiles, basic structural parts, jigs, power plants, fixtures, etc.

2.1.4 Filler material

The welding was carried out using a carbon steel wire electrode with a 1.0 mm diameter wire of type EN ISO14341-A: G3Si1, OK Aristorod 12.5. The wire chemical composition used for this thesis is shown in Table 3.

2.1.5 Gas type and compositions

Due to its advantageous properties, argon is one of the most widely used shielding gases. It has no chemical reaction with other materials, as it is an inert gas. The welding

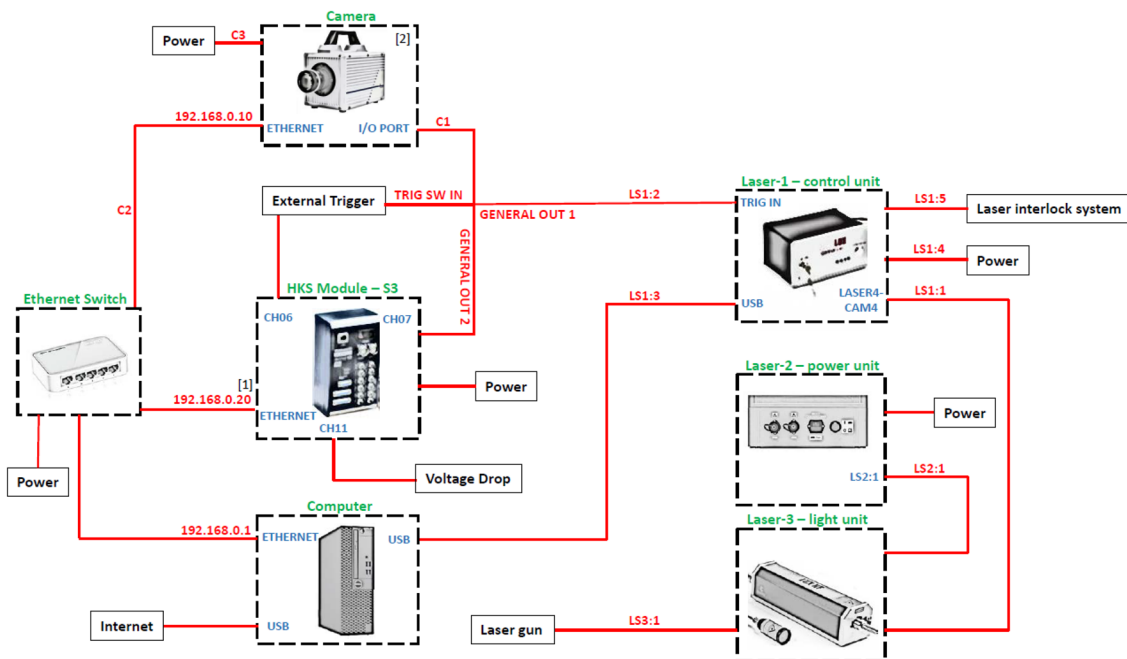


Fig. 3 Schematic setup of HKS weld analyst

Table 2 Chemical composition and mechanical properties of base material (S355J2)

Chemical composition (wt.%)					
Mn	Si	P	S	Cu	N
1.7	0.6	0.035	0.035	0.06	–
Mechanical properties					
Minimum yield strength (MPa)	Tensile strength (MPa)	Minimum elongation (%)	Charpy V-notch Temperature (°C)	Minimum impact (J)	
355	470–630	17	–20	27	

Table 3 Filler material composition typical wire composition (wt.%)

C	Cr	Cu	Mn	Mo	Ni	P	S	Si
0.08	0.03	0.07	1.46	0.01	0.04	0.013	0.012	0.85



Fig. 4 Carbon steel

properties are improved if CO₂ or a small amount of oxygen is included in the composition, particularly for short arc welding. A CO₂ concentration of up to 20% increases penetration (and reduces the chance of fusion failure), while a concentration of 5–8% reduces spatter. Therefore, a mixture of Argon 82% and CO₂ 18% is chosen for this experiment.

2.2 Method

The assessment of stability was carried out on carbon steel as shown in Fig. 4. The analysis was conducted with the two selected metal transfer modes (spray and pulse) using image and data processing equipment to identify stability conditions which are observable and evaluable. The choice of process parameters such as amperage, voltage, travel speed, shielding gas and flow rate, electrode extension, and so on, necessitates some testing to arrive at an acceptable set of conditions. Welding parameters were specified during the experimental phase to be not a single set of parameters but parameters “window” which will enable various disturbances of the process in a measurable way. Specific parameters were determined based on the response of the process in conjunction with its stability disturbances aspects. The weld type for the analysis was bead on plates with sandblasted surface conditions.

Three different welding voltage settings were employed (29, 31.5, and 32.5 V) alongside three different inductance control settings of 0, 60, and 95% inductance rate. A total of 15 experiments were conducted with the spray transfer mode and pulse transfer mode.

2.2.1 Voltage, current, and WFS regularity in terms of process disturbances and deviations

Analyzing voltage, current and WFS is essential in understanding the stability of a process as they serve as major indicators of stability. By monitoring these parameter influences on the arc using image processing, we can observe deviations and disturbances in the welding process. Variations in voltage will affect the metal transfer regularity as this also is an indicator of stability. The wire feed speed when increased or decreased affects the stability. An increase in the wire feed rate would increase the diameter of the molten drop thus a very high or low WFS

would generally result in the most unstable situations. It is important to note that there is a relationship between arc length and the stability of the process. When the arc length increases due to an increase in the CTWD, there can be a disruption in the process and thus result in varying current and voltage intensity. Simultaneously, when the voltage is too low, the arc length will be very short and as a result, the metal droplet would not have grown enough before it reaches the melt pool.

2.2.2 Spray transfer

Power source controls continuity of wire feed speed and arc length by regulations, but there is no regulation of voltage disturbances in spray arc as a consequence of physical and chemical processes in the arc during welding. The typical disturbance that is observable by analyzing image data and electrical signals is explosion in the arc that has random behavior and most commonly happens in two different stages of weld metal transfer. The first stage is the detachment of droplet from the wire tip and the second stage is actual entry of droplet in the molten pool. This behavior can be seen in the image data (see Fig. 5).

Explosions could be consequently observed by analysis of voltage. The good correlation between explosion and voltage peaks could be seen and each explosion results in a voltage change. These changes during welding have different characters depending on the stability of the process and could be determined as an important factor to be analyzed and characterized. Voltage disturbances have multiple variations that are measurable from obtained waveforms and therefore it was important to make a good evaluation. Voltage disturbances typically consist of positive and negative peaks. According to measurements, the

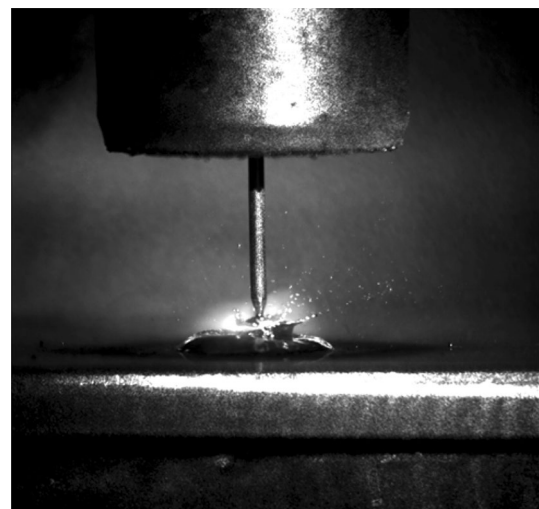


Fig. 5 Explosion taking place in spray transfer mode

negative peaks seem to correspond to an actual explosion while positive peaks are the consequence of the disturbance. The results showed that the degree of voltage disturbances depends on welding parameters and therefore the welding parameter “window” for analysis was determined to provide the scope of arc behavior with different stability characters. For this reason, the voltage and the inductance control were varied.

2.2.3 Pulse transfer

Stability behavior in pulse transfer mode is a different problem because of different character of the process and the fact that the process is controlled by the power source. Stability behavior is related to different factors compared to spray mode. Although the degree of the process control and regulation in pulse arc is very high, it is relatively easy for the process to become unbalanced in terms of regularity of metal transfer (one drop per pulse). Because from the preliminary analysis, it can be seen that pulse arc stability is to a high degree function of repeatability of certain current parameters and also unbalanced timing between peak and base current. These factors typically lead to unbalanced metal transfer. Additionally, the dynamics concept of regulation is having an impact on these aspects in terms of optimal metal transfer. Proposed factors for pulse arc stability characterization:

- Standard deviation (further SD) base current peak value
- SD of base current time duration
- SD of peak current peak value
- SD of peak current time duration

For the analysis, the linear pulse current waveforms (without exponential droplet detachment optimizers) were used alongside exponential waveforms. An example of a typical droplet detachment imbalance is displayed in Fig. 6.

2.2.4 Analysis of weld transfer modes

The mode of metal transfer has a huge influence on the stability of the GMAW process alongside the weld geometry. Numerous parameters influence the mode of metal transfer ranging from the current, voltage, shielding gas type and composition, etc. These parameters will influence the regularity, arc length, and volume of the molten drop. A laser backlighting high-speed camera videography is used to analyze the selected metal transfer modes. This is done by observing the droplet detachment sequences alongside the disturbances that occur during the metal transfer.

2.3 Analysis of spray transfer

Several welds were performed using spray transfer parameters with varying voltage and inductance control levels to characterize stability and understand the influence of voltage and inductance on disturbance levels and regularity in the welding process. Table 4 shows the parameters used for these tests. Each test consists of three identical tests in order to gain better statistics of analyses.

To measure these disturbances and be able to characterize stability, it was proposed that the following be measured: To be measured and calculated: measure the number of voltage disturbances per selected time (voltage peaks), measure maximum voltage peaks values per selected time, measure negative voltage peak values per selected time, measure the voltage amplitude (positive value plus negative value together), calculate the standard deviation of voltage–time durations without the occurrence of disturbance (with the threshold of ≤ 1 V disturbance), calculate the standard deviation of positive maximum voltage peak values, calculate the standard deviation of negative maximum voltage peak values, calculate the standard deviation of voltage disturbance amplitude (positive plus negative values).

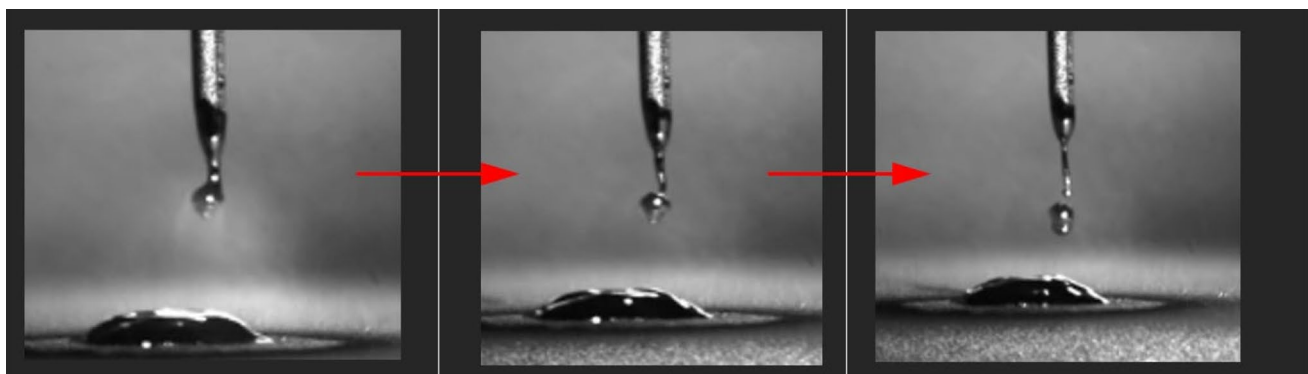


Fig. 6 Typical droplet detachment imbalance. Image data are gained in the experiment

Table 4 Table of spray welding parameters for varying voltage and inductance control rate

Test No	PS/Feeder	WMT (-)	FM/Diameter (type/mm)	WFS (m/min)	Voltage (V)	Current avg HKS (A)	Voltage avg HKS (V)	Travel speed (mm/min)	Inductance control rate (%)	Regulator type (no)	Gas (Ar/CO2%)	Gas flowrate (l/min)	Torch angle TD/PTD (°)	BM thickness/surfaces conditions (mm/-)
1	A500ix/Ro bustFeed	SPRAY	12.20/1.0 mm	12	29	231.27	28.82	11	60 (def)	10	Ar82CO218	15	15/0	8/Sand-blasted
				12	29	229.87	28.75	11	60 (def)	10	15	15/0	8/Sand-blasted	
				12	29	241.21	28.74	11	60 (def)	10	15	15/0	8/Sand-blasted	
2	A500ix/Ro bustFeed	SPRAY	12.20/1.0 mm	12	29	230.34	28.84	11	0	10	Ar82CO218	15	15/0	8/Sand-blasted
				12	29	230.22	28.8	11	0	10	15	15/0	8/Sand-blasted	
				12	29	238.81	28.8	11	0	10	15	15/0	8/Sand-blasted	
3	A500ix/Ro bustFeed	SPRAY	12.20/1.0 mm	12	29	211.61	28.79	11	95	10	Ar82CO218	15	15/0	8/Sand-blasted
				12	29	230.77	28.78	11	95	10	15	15/0	8/Sand-blasted	
				12	29	229.09	28.79	11	95	10	15	15/0	8/Sand-blasted	
4	A500ix/Ro bustFeed	SPRAY	12.20/1.0 mm	12	31.5	242.17	31.20	11	60 (def)	10	Ar82CO218	15	15/0	8/Sand-blasted
				12	31.5	241.41	31.19	11	60 (def)	10	15	15/0	8/Sand-blasted	
				12	31.5	233.08	31.21	11	60 (def)	10	15	15/0	8/Sand-blasted	
5	A500ix/Ro bustFeed	SPRAY	12.20/1.0 mm	12	31.5	247.71	32.2	11	60 (def)	10	Ar82CO218	15	15/0	8/Sand-blasted
				12	31.5	245.24	32.05	11	60 (def)	10	15	15/0	8/Sand-blasted	
				12	31.5	238.54	32.18	11	60 (def)	10	15	15/0	8/Sand-blasted	

The error threshold for calculation of all proposed factors has the value of 1 V.

To be plotted:

Plotted against three investigated voltage settings (29, 31.5, 32.5 V).

1. Number of voltage disturbances (≥ 1 V)
2. Maximum positive peak values (≥ 1 V)
3. Maximum negative peak values (≥ 1 V)
4. Amplitude of voltage disturbance (positive plus negative values)
5. Standard deviation of voltage–time durations without the occurrence of disturbance (without disturbances ≤ 1 V)
6. Standard deviation of positive maximum voltage peak values
7. Standard deviation of negative maximum voltage peak values
8. Standard deviation of voltage disturbance amplitude (positive plus negative values)

Plotted against three investigated inductance rate settings (0, 60, 95%).

1. Number of voltage disturbances (≥ 1 V)
2. Maximum positive peak values (≥ 1 V)
3. Maximum negative peak values (≥ 1 V)
4. Amplitude of voltage disturbance (positive plus negative values)
5. Standard deviation of voltage time durations without disturbance (without disturbances ≤ 1 V)
6. Standard deviation of positive maximum voltage peak values
7. Standard deviation of negative maximum voltage peak values
8. Standard deviation of voltage disturbance amplitude (positive plus negative values)

To be graphically analyzed from image data. Explosion size vs voltage maximum positive peak value.

Positive and negative peak values were recorded concerning their difference from average voltage value for each test.

2.3.1 Analysis of pulse transfer

As has been mentioned before, the pulse process stability was evaluated within the following factors:

- SD of base current peak value
- SD of base current time duration
- SD of peak current peak value
- SD of peak current time duration

For the analysis, the linear pulse current waveforms (without exponential droplet detachment optimizers) were used alongside exponential waveforms.

One set of parameters has been used, but to simulate two different stability conditions, it was decided to primarily vary pulse waveform character in terms of conditions for optimal droplet detachment. Welding parameters for the pulse process are listed in Table 5 below.

In order to evaluate the scatter of stability and visualize it, the proposed factors and their deviations were plotted against time (in a selected welding period time of 1.35 s) and also mapped in histograms with proportional distribution of deviation.

3 Results and discussions

Some data for quantitative analysis were acquired from welding of carbon steel utilizing spray and pulse transfer modes, which will aid in addressing the research questions and perhaps determining parameters that will aid in the characterization of stability.

3.1 Evaluation of results for spray transfer

Results from the analysis showed that negative parts of voltage disturbances significantly vary with average set voltage in terms of peak values. Inductance control does not seem to have a major influence on the behavior of negative peak values as seen in Fig. 7.

However, the scatter of values is wider with fast inductance control (60 and 95%) at the value of 29 V used. The scatter of disturbances, as well as a corresponding expression by standard deviation clearly show the better proportional distribution of peak values when higher set voltage is used. This is illustrated in Fig. 7. It can also be seen that the number of disturbances decreases as the set voltage value is increased from 29 to 31.5 V for a time period of 2.4 s. The decrease in disturbances continues with an increase in voltage from 31.5 V to 32.5 V. This characteristic is shown in Fig. 8. Inductance control does not seem to have a major effect on the number of disturbances happening in the same time period of 2.4 s. It was also observed that the average voltage amplitude (addition of positive and negative peak) decreased with increasing set voltage value as seen in Fig. 9. The average voltage disturbance amplitude was also noticed to be lower with 60% inductance control rate but relatively the same for 0 and 95% inductance control rate.

This confirms that the proposed characterization method utilizing maximum positive and negative voltage values, as well as mapping voltage amplitude and distribution of no disturbance times during the process, shows a

Table 5 Pulse transfer welding parameters

Test No	PS/Feeder	Waveform type	WMT (-)	FM/Diameter (type/mm)	WFS (m/min)	Voltage (V)	Travel speed (mm/min)	d (mm/min) Inductance control rate (%)	Regulator type (no)	Gas (Ar/CO2%)	Gas flowrate (l/min)	Torch angle/PTD (°)	e TD/PTD (°) BM thickness/surfaces conditions (mm/-)
1	A500ix/Robust-Feed	Linear	PULSE	12.20/1,0 mm	8,6	29	7	NA	10	Ar82CO218	14	15/0	8/Sandblasted
2	A500ix/Robust-Feed	Exp	PULSE	12.20/1,0 mm	8,6	29	7	NA	10	Ar82CO218	14	15/0	8/Sandblasted

very good response to the stability behavior of the welding process. This approach has already been used by Sato et al. [31].

3.1.1 Stability characterization with spray transfer mode

In order to determine the method of characterization of the stability of the process, variable parameters for spray transfer mode were selected to simulate different stability performances. The response of both voltage and inductance control proved to provide scope of stability conditions enabling to analyze factors that are correlated to arc disturbances and make a scientific assessment of their responses.

Analysis of the stability about qualitative aspects of the welding process has not been conducted, because full range of tested variable parameters provided acceptable weldability with the absence of defects. It was not needed to simulate the stability of the process beyond the weldable range to gain reasonably sufficient data on stability behavior to be analyzed, evaluated, and characterized.

3.1.2 Method of analyzing disturbances corresponding to explosions in spray arc

Spray arc requires the use of a high voltage and wire feed speed. These settings deliver a lot of heat to the workpiece and penetrate it. Generally, when the voltage is increased it changes the mode of the arc. It also influences the arc length, bead width, heat in the arc, etc. by increasing them. For this characterization, three different voltage settings 29, 31.5, and 32.5 V were applied in order to see how increasing voltage influences stability and disturbances in the arc. When analyzing voltage using image data and these disturbances occur, the response to this is always voltage change [32]. The power source works with voltage so if it senses a disturbance, it measures voltage and then compensates with the current. As voltage becomes higher the arc becomes more stable. Inductance is another parameter that was varied during the experimentation (0, 60, and 95). Inductance is the dynamic reaction of the power source [21]. It regulates the dynamic response of voltage and current during welding. It is a very important parameter in terms of control of the power source. Inductance also has a relationship with the current waveform. A low value of inductance would give a distinct and concentrated arc, but spatter will increase. A higher value of inductance gives a somewhat wider bead and a softer sound when welding.

Disturbances in spray arc usually occur in the form of explosions. We can observe from image processing in spray transfer two types of disturbances. One type is the explosion of wire tip weld metal which occurs directly

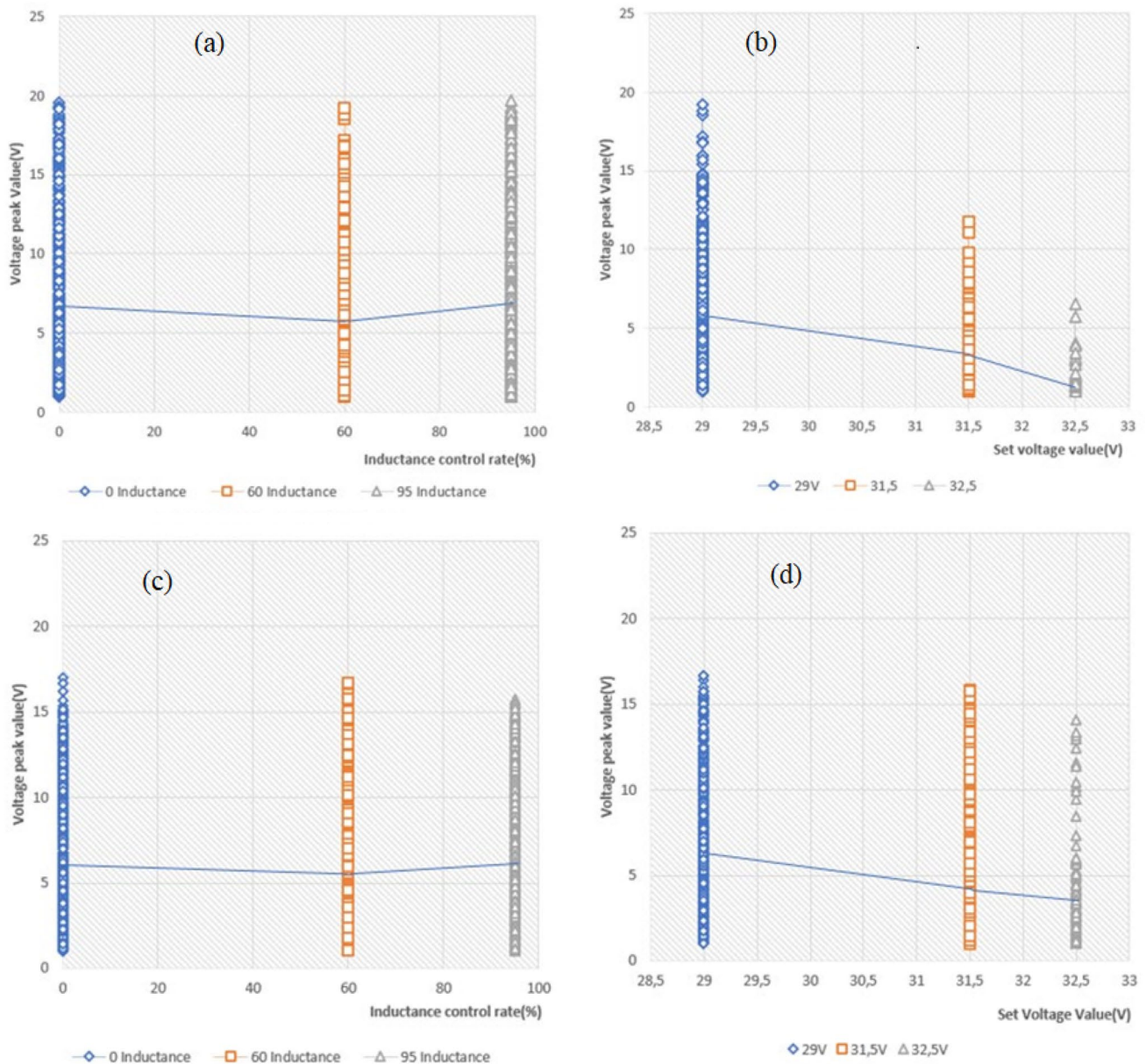


Fig. 7 Graphical representation of positive and negative peak values for set voltage values and inductance control rate: **a**: negative peak Voltage Values vs inductance control rate, **b**: negative peak

Voltage values vs set voltage value; **c**: Positive peak voltage values Vs inductance control rate; **d**: Positive peak voltage values Vs set voltage value

after droplet detachment. The second type is an explosion when the droplet is entering the weld pool. These disturbances (explosions) are said to be proportional to the amount of spatter in the process. This is illustrated in Fig. 10. This figure shows the timeline and the appearance of the explosion from the start (when voltage drops) to the end (when the voltage returns to average value).

In order to be able to measure disturbances, we need to first be able to identify them. Disturbances in the arc are usually seen in the form of voltage positive and negative peak fluctuations. These disturbances can be observed

using image data from high-speed cameras and quantified by measuring voltage disturbance positive and negative peak values recorded during the welding by the HKS weld analyst. Figure 11 shows an image illustrating how voltage disturbances (explosions) are measured in the spray arc.

It is believed that the negative period is likely the reaction of resistance change in the arc before explosion occurs. Explosion starts approximately in the negative amplitude (in maximum negative voltage peak) and ends when voltage balances approximately to average value. Positive amplitude seems to better correspond to

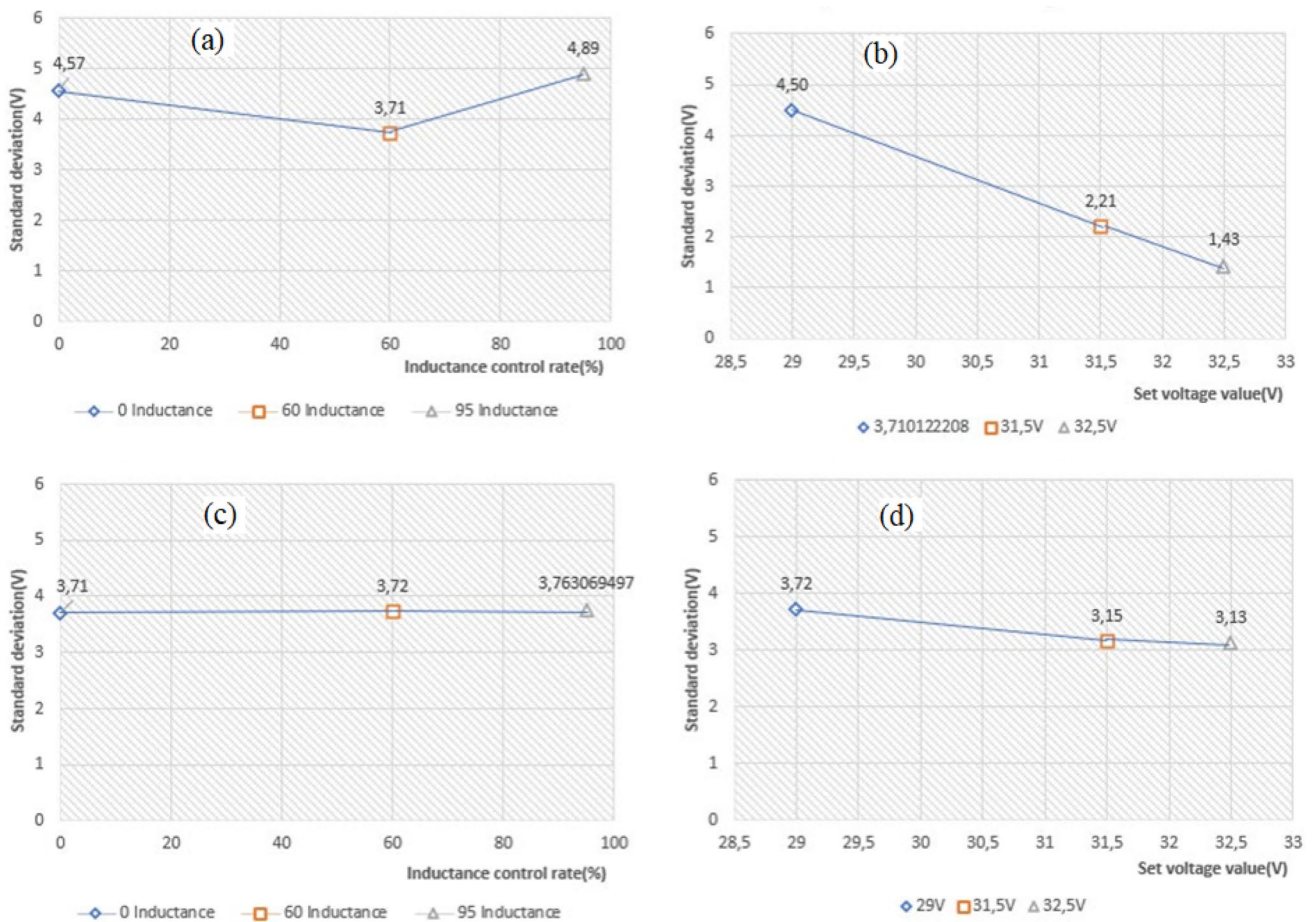


Fig. 8 Graphical representation of standard deviation of positive and negative voltage peak vs set voltage value and inductance control rate: **a**: standard deviation of negative voltage peaks Vs inductance control rate, **b**: standard deviation of negative voltage

peaks vs set voltage value; **c**: standard deviation of positive voltage peaks vs inductance control rate; **d** standard deviation of positive voltage peaks vs set voltage value

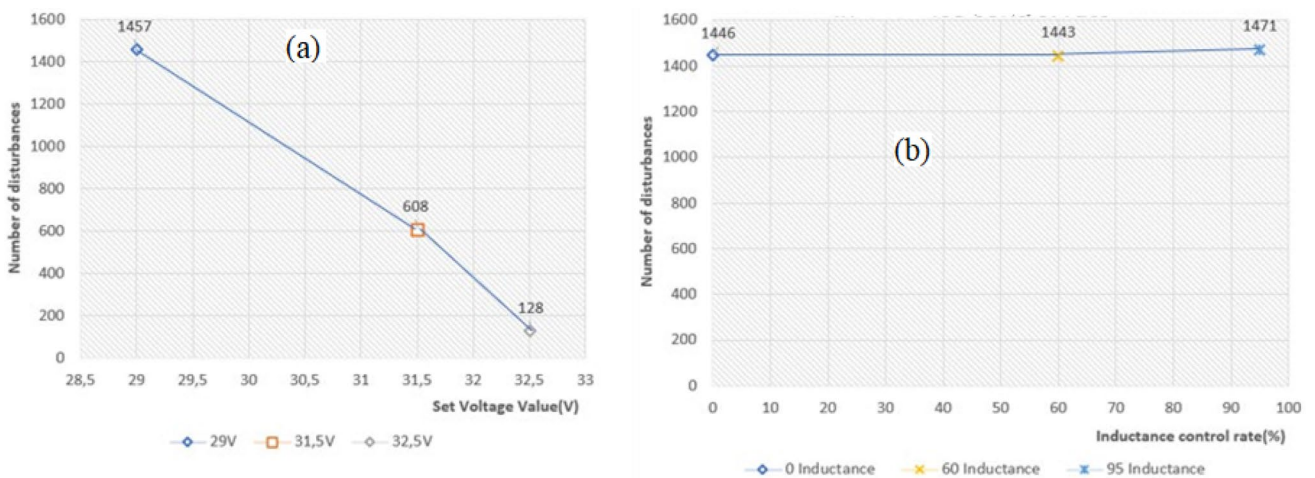


Fig. 9 Graphical representation of voltage disturbances vs set voltage values and inductance control rate: **a**, Number of voltage disturbances Vs Set Voltage value; **b**, number of Voltage disturbances Vs set inductance control rate

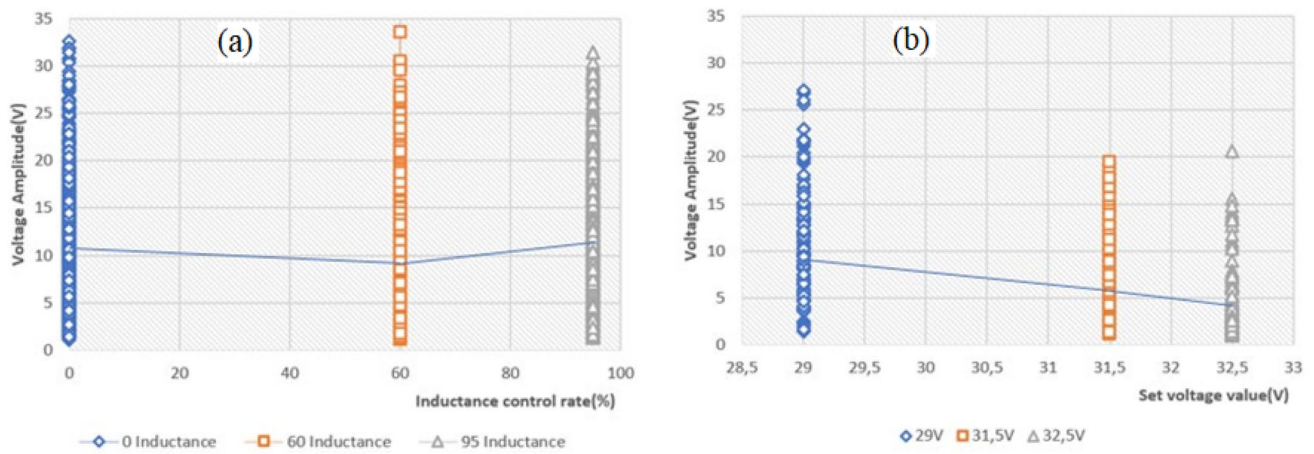


Fig. 10 Graphical representation of voltage amplitude vs set voltage value and inductance control rate: **a.** voltage amplitude vs set inductance control rate; **b.** voltage amplitude vs set voltage value

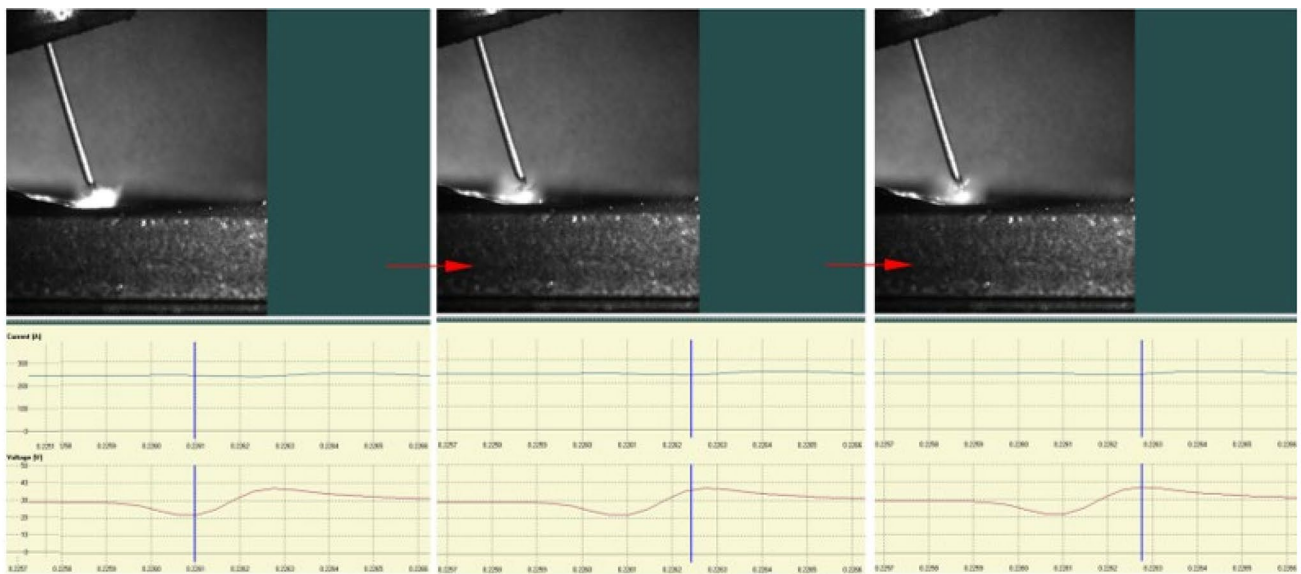


Fig. 11 Timeline and appearance of explosion from start to end

the size of explosion, while the negative period is important to know how much time the system has to react by countermeasure (countermeasure and possibility of the system to react and prevent explosion or reduce the degree of explosion) is not the part of this investigation. Only peaks with voltage increase or decrease of less than 1 V compared to the average voltage peaks were considered. This is because according to the analyzed waveforms within the scope of the tested parameters, voltage fluctuates around the average voltage setting and maximum positive and negative voltage values of these fluctuations do not exceed value of 1 V. The error threshold also has been determined based on the principle of

inductance regulation control which for used regulators is applying 1 V error detection.

3.1.3 Identification of combined voltage disturbance peaks (by maximum time difference between peaks)

The analysis of voltage disturbances (positive and negative voltage peaks which correspond to the disturbances in the process) happen in different patterns. Some peaks are solely positive, some are solely negative, and some are combined (amplitudes). From experiments conducted, it was observed that when these peaks are not further than 0.9 ms apart, they most likely cause one explosion and

could be considered one combined peak (positive plus negative peaks). When peaks are more distant, they are not considered combined amplitude peaks.

The maximum time difference between peaks to be considered as combined peaks, or have a mutual effect on the voltage disturbance, could be identified in the range of 0.9 ms- 1.0 ms. While the lower the values have been used for identification, two consecutive peaks beyond this time difference do not in principle act as a single voltage disturbance responding to one explosion in the arc. The time difference between peaks showed to be the optimal way for identification of combined peak, rather than slope steepness, or slope derivatives.

3.1.4 Explosion size vs voltage maximum positive peak value

Explosion levels in spray were visually analyzed from the image date and it has been concluded with a high degree of confidence that voltage peak values are proportionally increasing with the size of the explosions.

3.2 Evaluations of results for pulse transfer

Two different current waveforms were compared in terms of evaluating effects on stability. The linear waveform (W no.1), which is the conventional type of waveform was compared to the exponential waveform (W no.2) with optimized droplet detachment. After analyzing plotted results and calculated deviations, it can be concluded that: i) W no.1 shows superior stability in base

current values over analyzed time compared to W no.2. On the other hand, W no.2 shows a more regular distribution of peak current. This can be explained by the different principles of software regulation in power sources. This is represented in Fig. 12, and Fig. 13. Those figures display a linear and an exponential waveform distribution histogram chart, respectively. These charts show the base current, pulse current, pulse duration, and base current time duration distribution. It can be seen from these figures that the proportional distribution of values for Fig. 13 (exponential waveform) is better than for Fig. 12 because the standard deviation is lower. ii) While the differences between waveforms in pulse peak duration are not significant (3%), relatively big differences could be observed in base current duration times (23%). This factor is very important in terms of stability of droplet detachment because it directly relates to the dynamic forces during the droplet detachment phase and accumulation of liquid weld metal on wire tip by surface tension and consecutive formation of droplets (see Fig. 14). Figure 15 shows a linear and exponential waveform for the base current, pulse current, pulse current duration, and base current time duration. Displayed on the image are the average values of these peaks, minimum value, maximum value, and the SD of each of these parameters. iii) Results show that W no.2 could be considered as the waveform that provides more stable conditions for pulse arc. This can be confirmed by image analysis where it is visible that the balance of pulse weld metal transfer is optimal in terms of one droplet per pulse transfer (see Fig. 16).

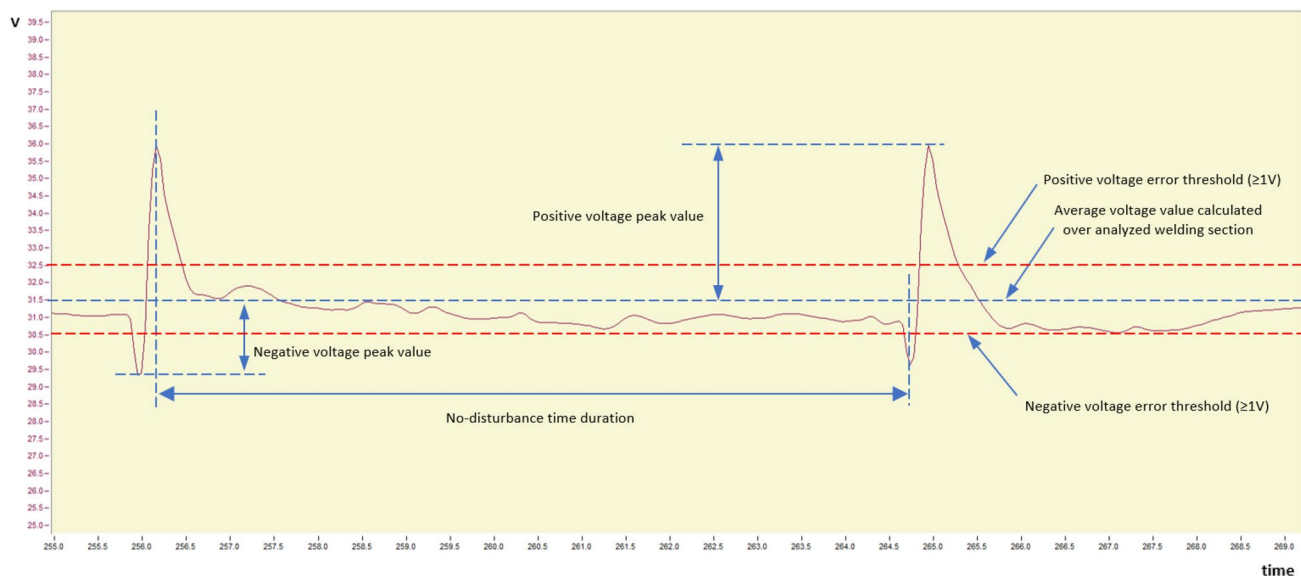


Fig. 12 Method of analyzing voltage disturbances responding to explosions in the spray arc

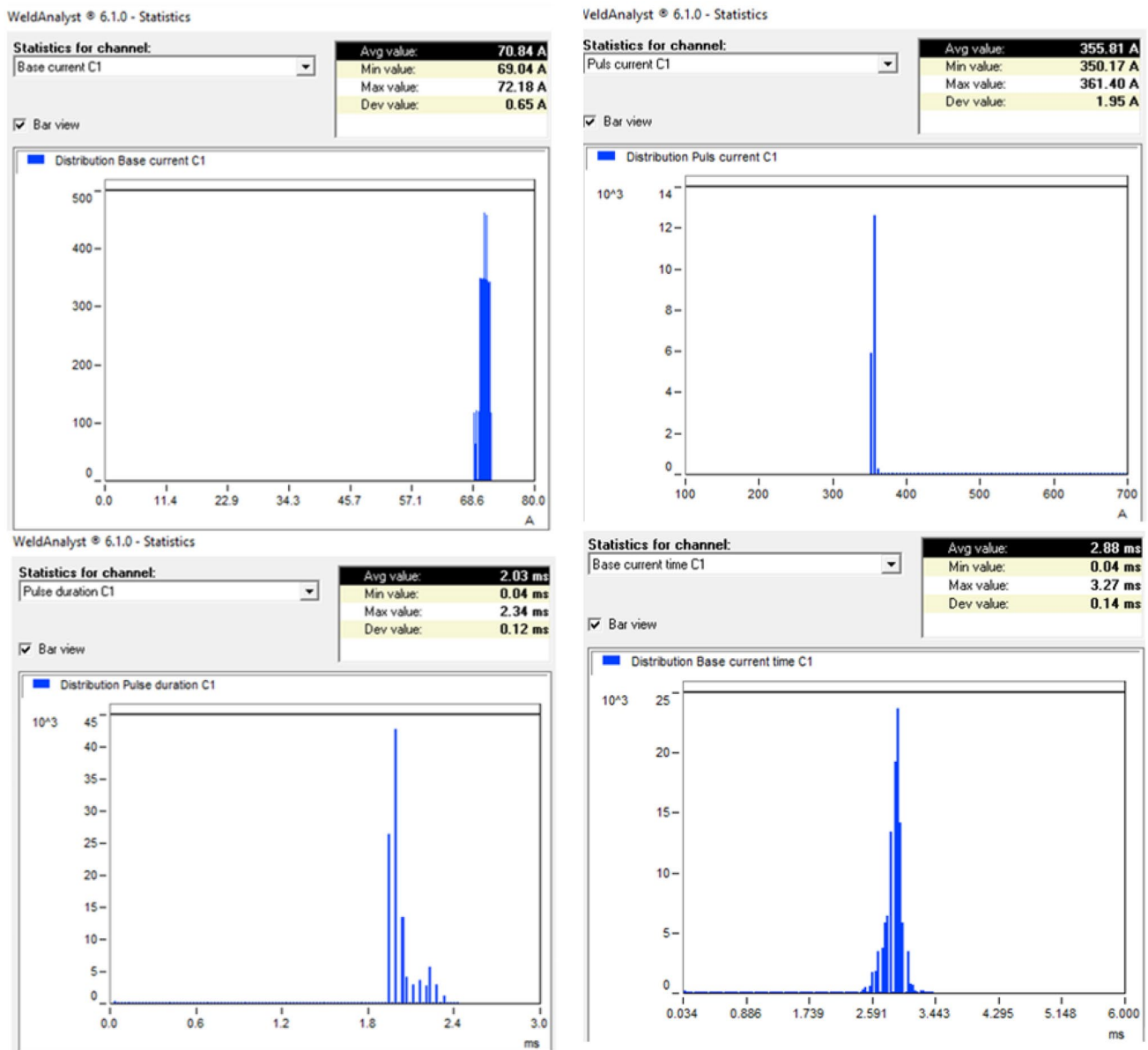


Fig. 13 Linear waveform distribution chart as generated from web analyst

3.2.1 Stability calculation and scoring

When it comes to stability, there is no singly accepted factor used for quantifying the stability of a process. This is because stability can be perceived in different ways depending on the specification of the manufacturer or the user based on the application. Generally, stability can be classified and scored in two different ways: stability as a performance character (ST1), and stability as regularity of the process (ST2).

Stability as a performance character focuses on stability indicators such as spatter presence, hardness of arc,

and smoothness of the process. Just a small proportion of the industry classify stability based on these.

Stability as regularity of the process centres on repeatability and steadiness of electric parameters, variation of process disturbances, and uniformity of the process. The majority of the industry considers stability to fall into this category.

3.2.2 Method of establishing stability scoring

Stability calculation for 3 different tested voltage values was carried out. A range for every factor that is relevant

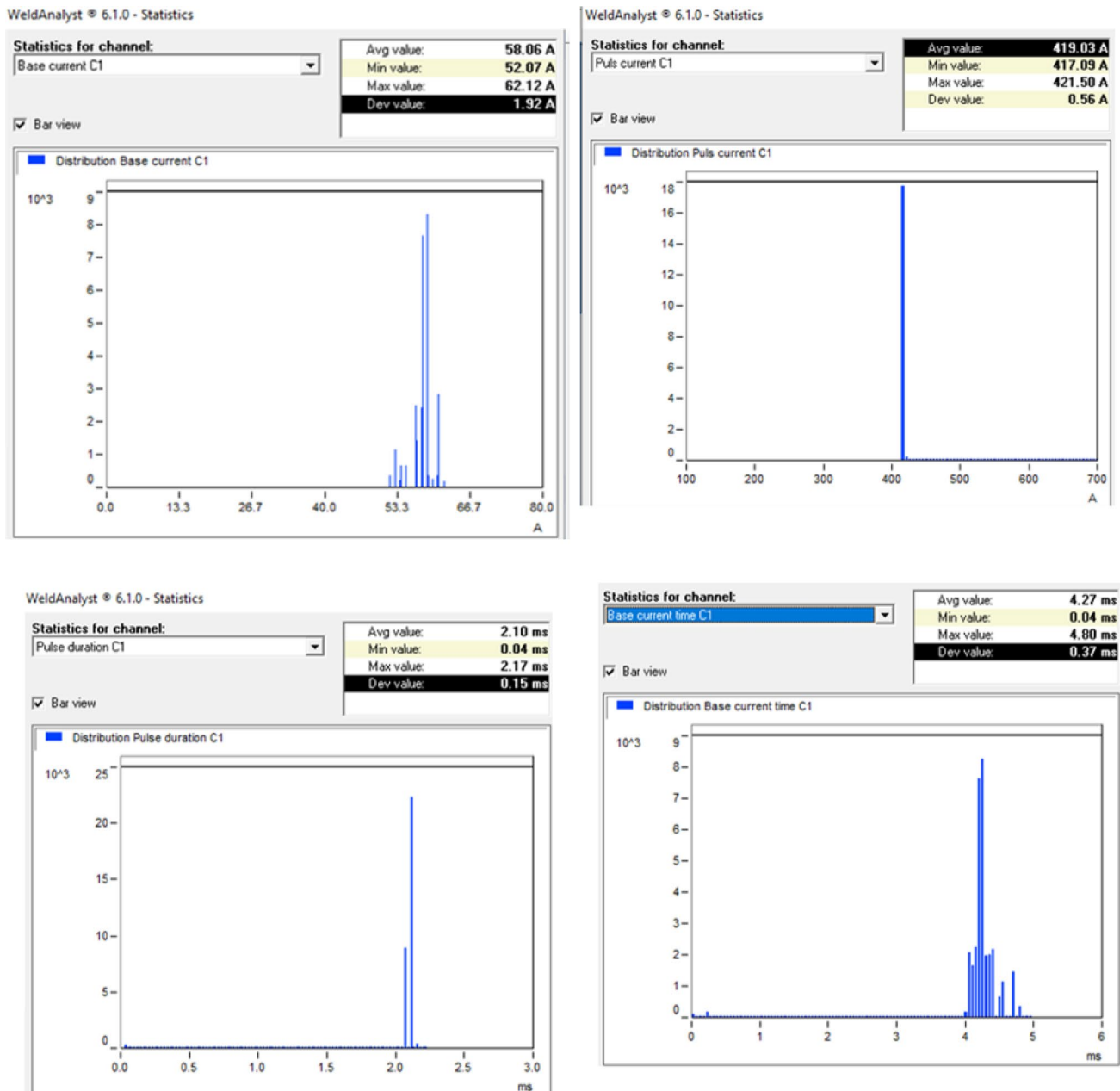


Fig. 14 Exponential waveform distribution chart as generated from web analyst

was created and this range has its minimum to maximum value. The minimum value is always zero and maximum value is different for different factors (it can be the same for some factors). This range is determined based on how the specific factor scatters over the range of stability in applicable range.

Relevant factors are then converted to percental values conforming to a specific range, which makes a score for specific factor.

Selection of factors is determined based on their influence on stability in 2 different groups (ST1, ST2). Regarding

stability groups, it is necessary to split them because there are two different ways of recognizing stability in industry today (one is more welding quality-related (spatter, hardness of arc, coarseness of the process), which is a minor proportion of industry/applications and another one is related to process regularity, which is major proportion, this type would be representing stability as regularity of the process (repeatability and steadiness of all parameters, fluctuation of process disturbances, uniformity of the process). Each of these stability characteristics is correlated to different factors that we calculate.

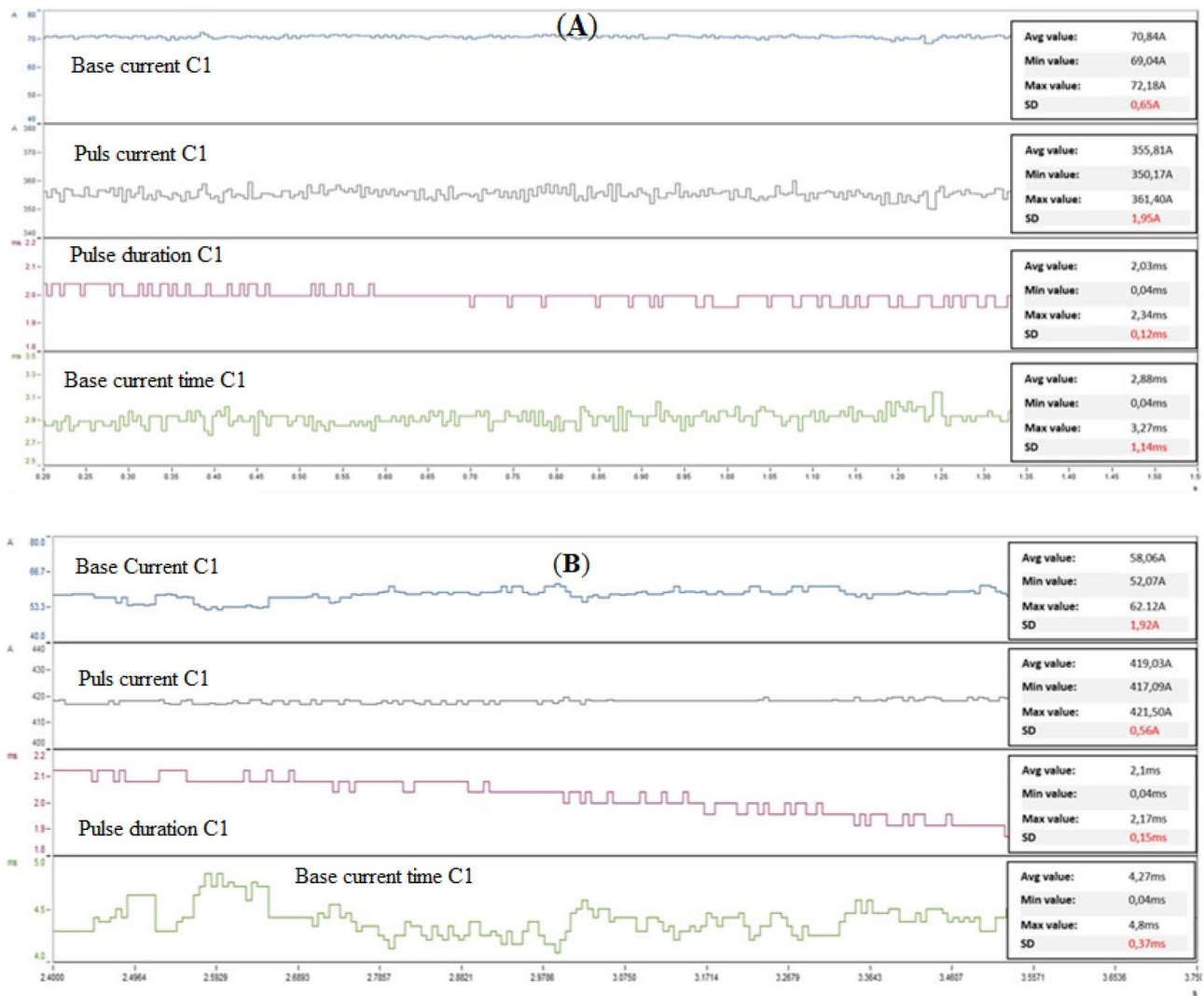


Fig. 15 Image of a time duration of 1.35 s for: A- Linear waveform and; B- Exponential waveform

The percentual weight for each factor has been specified. The weight factor was estimated based on relevance of the factor on stability based on the analyzed image and data.

After all relevant factors are scored, overall score is calculated as weighted average of selected relevant factors in relevant weight.

Below is the formula for scoring stability.

$$ST1 = (N_{NP} * 0.3 + N_{CP} * 0.1 + aveU_{NP} * 0.3 + inverseavet_1 * 0.2 + STDEVU_{NP} * 0.1) * 10 \tag{1}$$

$$ST2 = (STDEVI * 0.33 + STDEVU * 0.3 + STDEVU_{NP} * 0.33) * 10 \tag{2}$$

N_{NP} : Number of negative voltage peaks; N_{CP} : Number of combined peak.

Figure 17 shows a graph illustrating stability score results.

From the stability score calculation ST1;

Stability score ST1: 29 V = 9.90.

Stability score ST1: 31.5 V = 4.80.

Stability score ST1: 32.5 V = 1.80.

From the stability score calculation ST2;

Stability score ST2: 29 V = 6.68.

Stability score ST2: 31.5 V = 3.07.

Stability score ST2: 32.5 V = 2.33.

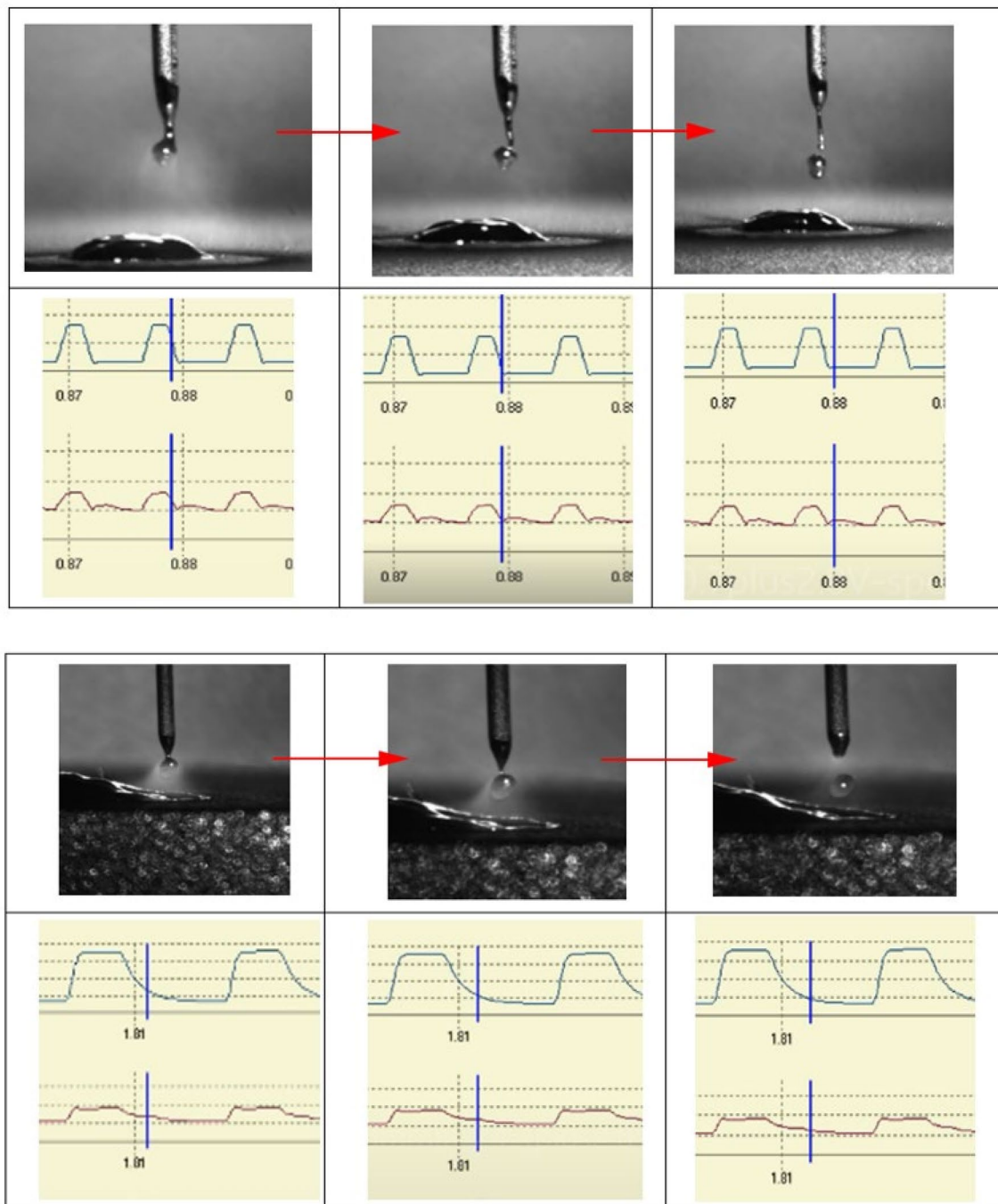


Fig. 16 The top image shows droplet detachment sequence with a linear waveform and the bottom exponential

4 Conclusion

The methods described in the article are based on the measurement of the welding current and welding voltage varying with time. The stability of the welding process can be determined in several ways.

In the characterization of the stability of spray transfer, only the voltage peaks were evaluated and not

the current peaks. This is due to the fact that in spray transfer, the power source operates with a voltage; the error threshold was calculated based on the inductance control principle that uses 1 V error detection for the controllers used; from the analyzed image data, it was observed that two consecutive peaks, separated by about 0.9 ms, each behave in principle as a single voltage disturbance in response to a single arc explosion. It

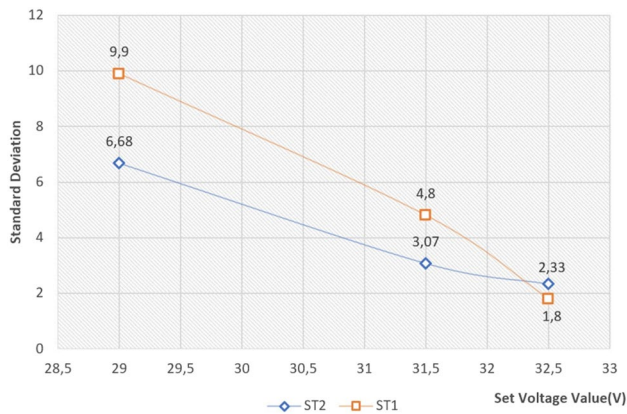


Fig. 17 Stability score calculation results for ST1 and ST2

was observed from high-speed camera image data that the larger explosion sizes correlated with the magnitude of the voltage fluctuation at that time. Thus, it can be concluded that there is a relationship between voltage fluctuations and explosions that occur during metal transfer. Thus, a larger explosion size coincided with a larger voltage peak.

For pulse transfer, it was observed that the exponential waveform had a smoother distribution of peak current, although the linear waveform showed better stability of the base current values over the analyzed time. The proposed characterization method needs to be completed with variable coefficients and threshold values that would allow the method to be applied to cases where the stability of the process varies due to various aspects, such as shielding gas, type of filler material, quality of the base material and its surface condition, among others. In this way, it will also be possible to incorporate the variability of the qualitative aspects that occur in response to the deterioration of stability.

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Declarations

Conflict of interest The authors declare that they have no conflicts of interest to report regarding the present study.

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