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# Stability on the GMAW Process

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## Abstract

The gas metal arc welding (GMAW) process is highly used in industrial production; therefore great efforts are made to select the appropriate procedure to ensure the highest quality. An area of study directly correlated to the quality of GMAW and widely studied is the control of process stability. The objective of this chapter is to present a bibliographical review of the scientific literature related to qualitative and quantitative indexes to evaluate the stability of the GMAW process. The documents present a compilation of the factors that affect stability, stability indexes, and, finally, a synthesis of the study. With a review of the literature, it was concluded that the highest percentage of investigation was aimed at the study of metal transfer stability, specifically with the short-circuit transfer mode. It is also evident that the main processing techniques to develop the indexes were the mathematical formulation; the statistical analysis; image processing; and monitoring of acoustic signals. In this text, the discussion surrounds the papers, the thesis, and other documents found on the theme.

**Keywords:** welding, GMAW, quality index, GMAW, process stability

## 1. Introduction

GMAW as a welding process presents a high degree of production, reliability, and automation capacity. With the appropriate parameter configuration, it allows welding in almost all positions and with almost all existing metal alloys. One peculiarity of the GMAW process is that, depending on the intensity of the current and voltage, different types of metal transfer can be observed. The metal transfer mode characterizes the way molten metal is deposited. The three main modes of metal transfer are short circuit, globular, and spray. The most relevant parameters involved in the process can be mentioned: amperage, voltage, welding speed, and stick out. Another peculiarity is that the process can be defined as chaotic; involves the interaction of several nonlinear welding variables; and presents a stochastic behavior. Therefore, great efforts are made to select the appropriate procedure to ensure the highest quality.

Quality can be defined as the union of a client's requirements with respect to a product. In the particular case of welding, the main objective is to get a weld bead as close as possible to the requirements. The welding quality can be monitored in two moments: online while the process is running and offline after the welding bead is obtained.

The offline evaluation considered geometric factors such as proper penetration, reinforcement, and the length of the pieces. Destructive tests can be carried out and

consist of taking samples of weldments to evaluate the metallic continuity, mechanical strength, and other determining factors for the correct performance in service. Sometimes these tests lead to the destruction of the body tested. On the other hand, Wu et al. [1] affirm that online quality control allows the saving of financial resources through the reduction of defects in the production line. For this purpose, sensors for visual imaging, sound acquisition, infrared cameras, and ultrasonic sensing methods have been implemented.

One concept that is strongly correlated to the online quality is the control of the process stability. According to Ponomarev [2], the stability of the GMAW process is evaluated online by three factors: metallic transfer regularity, arc stability, and the operational behavior of the welding process. Meneses [3] also ensures that the higher the transfer stability, the higher the penetration and the lesser the amount of spatter.

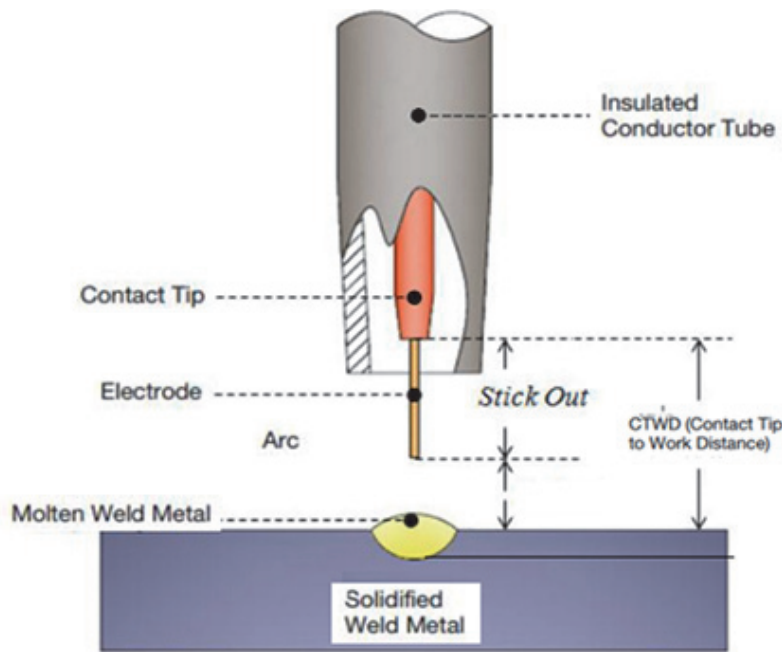
The objective of this work is to present a bibliographical review of the scientific literature related to weld quality evaluation, focused mainly on those studies that present qualitative and quantitative indexes to evaluate the stability of the GMAW process. The chapter is structured as follows: Section 2 discusses Stability Control in the GMAW process; Section 2.1 discusses GMAW process operation; Section 2.2 discusses factors that affect stability; Section 2.3 presents a Summary of Stability index; and finally, Section 3 reveals a synthesis of the study and future research directions.

## 2. Stability control in the GMAW process

### 2.1 GMAW process operation

GMAW process is characterized by producing an arc between a consumable electrode that is constantly fed, a protective gas, and the piece to be welded, as represented in **Figure 1**.

Conductor tube: It is a welding torch component device and fulfills the function of guiding the gas flow in the welding process.



**Figure 1.**  
*Basic diagram of the MIG/MAG process (modified from [4]).*

**Contact tip:** It is a torch device that has the function of guiding and supplying voltage to the wire.

**Electrode:** It is the consumable copper-coated steel electrode that melts with the electric arc and transfers to the melting pool.

**Workpiece:** composed of the metal bodies to be joined by the weld.

**CTWD (contact tip to work distance):** It is often confused with the distance between the contact tip and the work piece, which coincides when the nozzle front cut is also the same as the contact tip front cut.

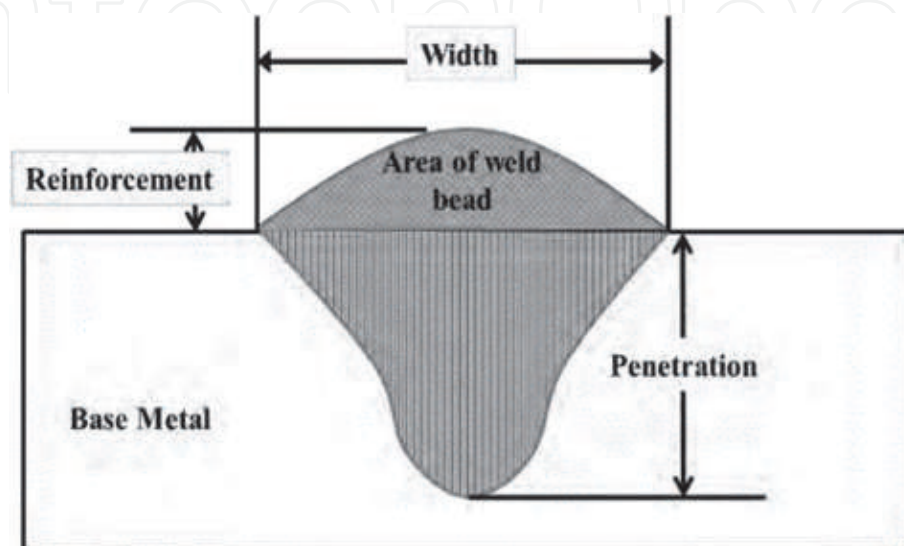
**Stick out:** It is the length of free wire after it has passed through the contact tip.

The gas composition aims to stabilize the arc and protect the welding material from atmospheric gases such as nitrogen and oxygen, which can cause fusion defects, porosity, and weld metal embrittlement if they come in contact with the electrode, the arc, or the welding metal. Depending whether the gas is inert (Ar or He) or active (CO<sub>2</sub>, or mixtures including N<sub>2</sub> or O<sub>2</sub>), it can be classified as metal active gas (MAG) or metal inert gas (MIG).

The weld bead geometry depends directly to the parameters that govern the process. **Figure 2** outlines these geometric parameters in the cross section of a weld bead. The most important parameters affecting penetration and geometry in the GMAW process are welding current, arc voltage, torch travel speed or welding speed, stick out, torch tilt, and the diameter of the electrode.

According to [6] the process parameters of GMAW can be divided into five basic groups (as shown in **Figure 3**):

- Fixed, that cannot be modified by the operator and it is defined in the process design.
- Adjustable online, that can be modified during the process.
- Adjustable offline, that can be modified only before starting the process.
- Quantifiable online, that is measurable during the process.
- Quantifiable offline, that is measurable only after the process ended.



**Figure 2.**  
 Weld bead geometric characteristics [5].

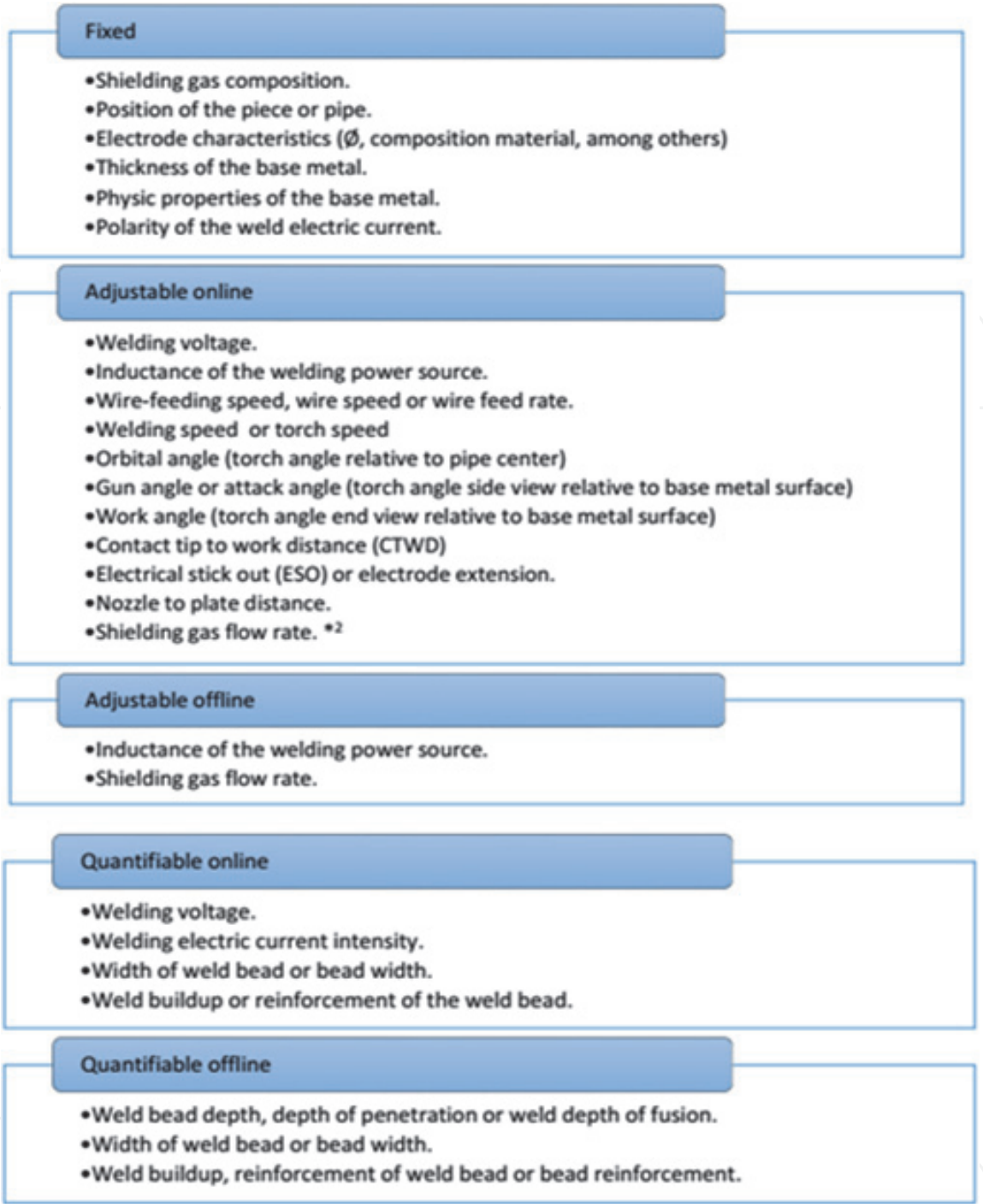


Figure 3.  
Classifications of GMAW parameters [6].

2.2 Factors that affect the stability

The operational behavior has a big influence on stability. If the gas is not supplied accurately, the arc may not initialize, there would be no stable or continuous plasma ionization, and the protective effect will be affected; nitrogen, oxygen, and water vapor enter the welding region and directly contact with the arc and melting metals, reducing the arc stability and forming a variety of welding defects. In the same way presence of grease, paint, dust, humidity, and extreme temperature produce a variation on the welding voltage.

But arc stability is directly influenced by the parameters of the process. It is possible to mention that a relationship exists between the arc length and process stability. Increasing the length of the arc (due to the increase of the contact nozzle

to work the piece length) will lead to a destabilization of the process, producing variations in the intensity of the welding current and the arc voltage. At the same time, when the voltage is too small, the arc length is short, so the droplet does not fully grow and then contacts with the molten pool.

The parameter's wire feed speed also has an influence. By increasing the feed rate of the wire, the diameter of the drop decreases; very high or lower values coincide with the most unstable conditions. But the degree of this influence depends on the shielding gas used and the welding voltage.

Furthermore, the variation of the current affects the metallic transfer regularity, and furthermore the transfer regularity reflects the stability of the process. Then it can be said that these factors are going to be influenced by the dynamic behavior of the GMAW welding process, particularly by the physical variations during the different transfer modes. Consequently, to understand how these factors influenced the stability, it is necessary to delve into the characteristics of the metal transfer.

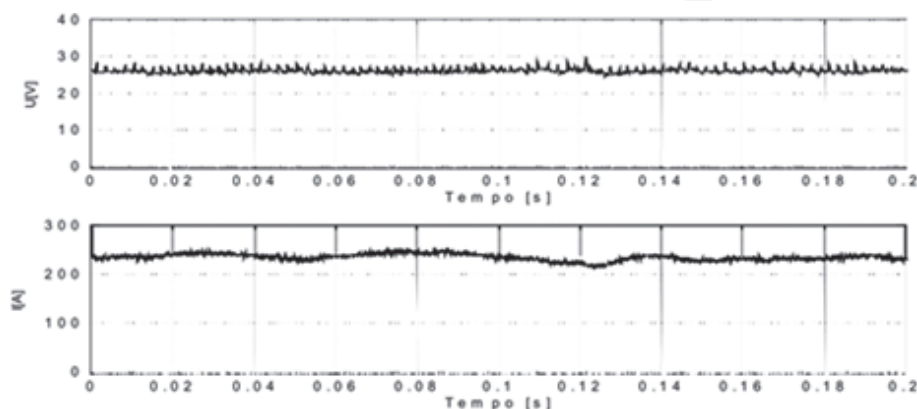
The metal transfer has a direct influence on the stability of the arc and final geometry of the weld bead. The metal transfer is controlled by several parameters such as current, voltage, electrode diameter, and shielding gas composition. It directly influences the way that metal droplets are transferred; the uniformity and the volume of the drop; and variations in arc length.

The three first transfer modes are short circuit, globular spray, and pulsed GMAW. In addition to these modes of transfer, there are others classified as free-flight transfer modes which happen when the arc voltage is high and includes repelled globular, projected spray, streaming spray, and rotating spray. The present study focuses on the three first natural modes of transference.

Spray transfer is characterized by small, uniform drops with diameters close to the size of the electrode. This transfer is obtained with high intensities and high voltages; its current intensities are from 150 to 500 A and its voltages from 24 to 40 v. Inert shielding gas favors this type of transfer. The process is presented with high arc stability, with high currents and deep penetration in the workpiece, and a high frequency of detachment. It allows high penetration to be achieved. Voltage and welding current oscillograms do not differ significantly, as shown in **Figure 4**.

In the globular transfer, the drop grows until exceeding the size of the electrode, and the detachment occurs by the action of the gravitational force. Typical parameters in globular transfer are voltage 20–36 v, current intensity 70–255 A. It has been unwanted in the industry for its instability and high grade of spatter. During this transfer mode, the output currents are kept oscillating depending on the detachment of the drop, as shown in **Figure 5**.

Pulsed transfer is considered a particular case of spray transfer but is characterized by great stability that is achieved by controlling the process variables, in



**Figure 4.**  
 Waveform factors spray transfer mode [7].

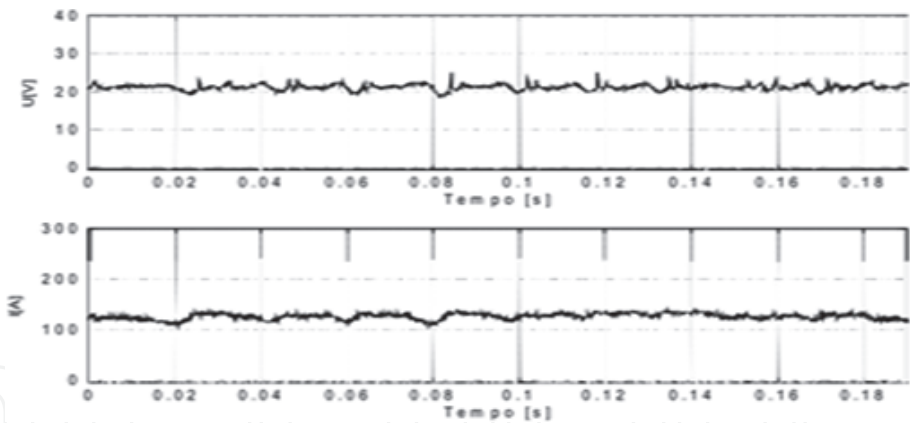


Figure 5.  
Waveform factors of globular transfer mode [7].

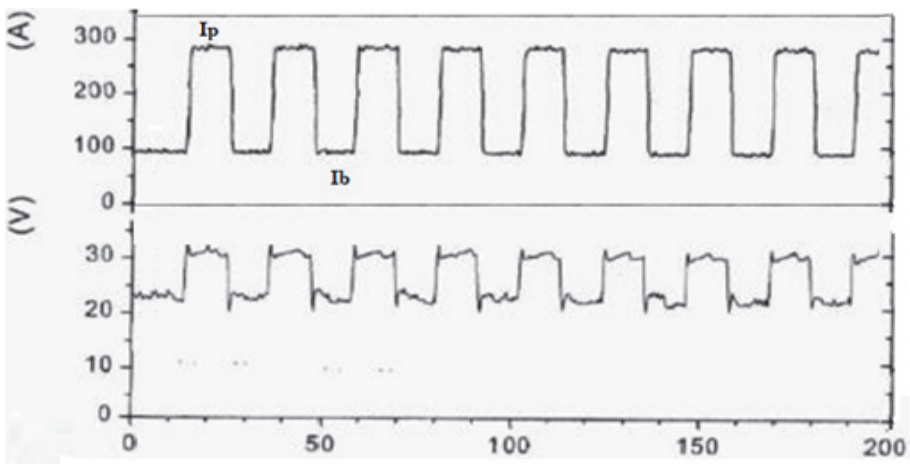


Figure 6.  
Waveform factors (modified from [8]).

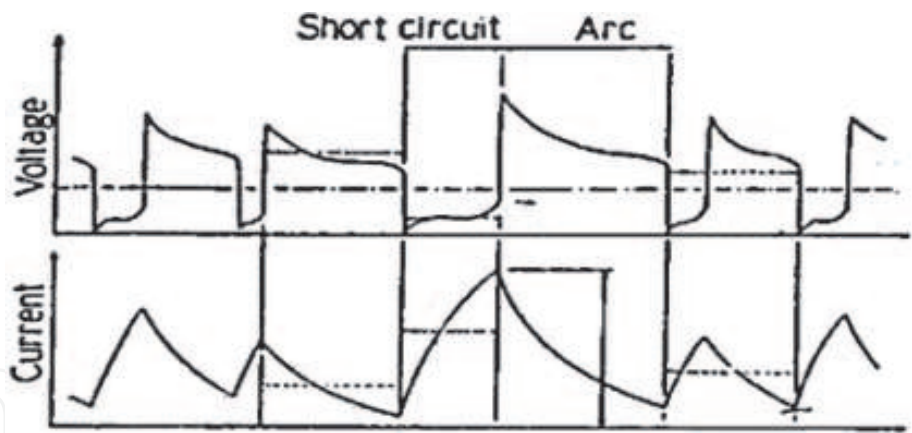
particular the current. The welding equipment generates two levels of current. In the first, the base current ( $I_b$ ) is kept low so that there is no transfer, but only the onset of wire fusion; in the second, the peak current ( $I_p$ ) is higher than the globular transition current causing the transfer, under optimal operating conditions, of a single drop. Typical parameters in pulsed transfer are voltage 20–30 v and current intensity 100–300 A, as shown in **Figure 6**.

Another parameter that influences the stability of the process is the transition current, which changes the frequency and diameter of the transferred drops.

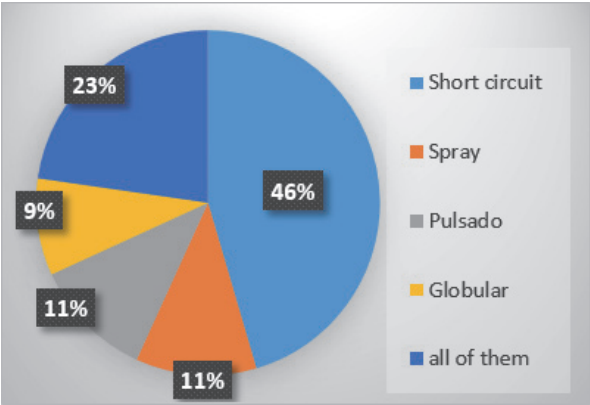
In case of a given current of short-circuiting transition, the droplet transfer exists in the form of short-circuiting, and the welding is stable. When the welding current increases, the droplet transition changes from the short-circuiting mode to the mixed mode, so the welding process and electric signal become unstable.

On the other hand, the globular-spray transition current also presents instability; a big number of spatters but the arc is no longer extinguished. Studies show that with the increase of  $\text{CO}_2$  in the gas mixture, an increase of the transition current is produced.

Finally, a peculiarity of the short-circuit transfer mode is the existence of regular contact between the electrode and the workpiece. Typical short-circuit parameters are voltage 16–22 v and current intensity 50–150 A. When the short circuit occurs, the arc is extinguished establishing two characteristic phases: the arcing period and the short-circuit period. Droplet growth occurs in the arcing period, whereas during the contact period, the metal is transferred. Also, the voltage and current oscillate to high and low at the same frequency of the metal transfer (**Figure 7**).



**Figure 7.**  
*Waveform factors (modified from [9]).*



**Figure 8.**  
*Papers classified by transfer modes.*

Furthermore, a relationship between the waveform factor of the short circuit and the arc stability exists. Some parameters (relating to time and current) used to quantify stability are easy to calculate from the waveform factor, as the short-circuit time, the arcing time, the transfer period, and the short-circuit frequency. Mita et al. [9] also affirm that the correlation between those parameters and the stability becomes weaker with increasing current.

### 2.3 Summary of stability indexes

Using the abovementioned concepts, several indexes have been proposed to infer the stability and quality of the welding process. They were calculated using image processing techniques, acoustic monitoring, and analysis of the electrical signals. **Figure 8** shows the percentage of papers classified by transfer modes, and it was found that the highest percentage of indexes focused on the short-circuit transfer mode.

#### 2.3.1 Statistical analysis to identify disturbances

Knowing that a signal behaves according to a stochastic process, it is possible to determine a probabilistic model and apply some algorithms to process this signal. Hence, several works have focused on the study of the electrical signals at the moment of disturbance, using a statistical treatment.

Adolfsson and Bahrami [10] calculate the variance of weld voltage (every 1024 signals). The study validates the hypothesis that the instability of the process

(caused by disturbances) correlates with a decrease in the variance of the weld voltage; in a similar manner, the short-circuit transfer rate decreased; conversely, no decrease occurs in the estimated variance of the weld current. The results obtained were used in the development of an online fault detection algorithm. This work shows a promising stability index but is only oriented to short-circuit transfer mode and was not extended to other transference modes. Note that the moments of disturbance were caused by making cuts in the workpiece and not varying input variables of the process such as wire feed speed, welding speed, and contact tip to work distance (CTWD), which also influences the stability.

Luksa [11] calculates the mean value of short circuit; the variance of welding current; the time of arc burning; and the short-circuit frequency values (every 2200 signals samples). He identifies two types of disturbances those caused by external factors such as grease and paint that affect the gas shield of the welding arc and a second group caused by variations in the wire extension. As was mentioned in the previous work, the author indicates that the variance of weld voltage decreased in the disturbance moment. But he also affirms that the short-circuit rates increase and optimal process stability can also occur during step disturbance, which contradicts the results found by [10]. An interesting contribution of this work is the study of the correct data window size since very large or small data window size can lead to erroneous stability results.

Finally, Wu et al. [12] used statistical process control (SPC), creating a sequential chart of the welding voltage and current (every 2000 signals). Coinciding with the index previously presented, a decrease in the estimated variance of the welding voltage occurs during the disturbance step. They also understand as a result an increase in the kurtosis for both the welding voltage and current. The results were generalized for the three main transferences modes and used in the construction of an SPC.

### 2.3.2 Arc stability

In 1988, the authors Mita et al. [9] enunciated the correlation between the stability of the arc and standard deviation of the arcing time; the standard deviation of short current; and the average value of short-circuit frequency. They used linear regression to prove this correlation and to create a new stability index. They showed that short-circuit frequency is influenced by several welding parameters mainly the wire feed rate and the arc voltage. Also, affirm that the stability of the process grows when the standard deviation of the short-circuit frequency decreases. However, the proposed index was tested in all current ranges, and the authors conclude that good arc stability can be obtained in all transfer modes.

Hermans and Ouden [13] propose a criterion for arc stability (Eq. 1, **Table 1**), based on the short-circuit frequency using the relationship between the arc time and the short-circuit time. To do this, they analyzed the behavior of the weld pool taking images with a high-speed camera. The authors concluded that the moment in which the oscillation frequency of the welding pool and the short-circuit frequency are synchronized, the greatest stability is reached.

Ogunbiyi and Norris [14] perform a summary of several criteria presented by other authors and propose three indexes to calculate the stability of the metal transfer. These indexes are Transfer index (Eq. 2, **Table 1**), transfer stability index (Eq. 3, **Table 1**) and dip consistency index (Eq. 4, **Table 1**), which are based on the correlation between metal transfer modes, arc stability and current waveform. The study confronts the three main modes of metal transfer, an advantage in relation to other studies. They calculate the indexes based on the relationship between minimum, mean, and maximum welding current. The indexes and the mathematical

Objective	gas	Transfer mode	Equation	Measured parameters and Variables
Calculate Short Circuit frequency	CO2		short circuit frequency $Fs = \frac{1}{(ta+tc)} \quad (1)$	When $ta$ is arc time and $tc$ Short circuit time
Identification of the metal transfer mode and arc stability	Ar+Co2 Ar+He+CO2	Short Circuit Globular Spray Short Circuit	Transfer index $TI = 1 - \frac{I_{min}}{I_{mean}} \quad (2)$  Transfer stability index $TSI = 1 - \frac{I_{max}}{I_{mean}} \quad (3)$  Dip consistency index DCI $DCI = 1 - \frac{V_{dk}}{V_{mean}} \quad (4)$  Power ratio $PR = \frac{I_{dk} \cdot V_{dk}}{I_{mean} \cdot V_{mean}} \quad (5)$	$I_{mean}$ =average of the welding current $I_{max}$ =maximum value of the current $I_{min}$ = lowest value of the current. $V_{mean}$ =average of the voltage $V_{dk}$ =average of all the voltage $I_{dk}$ =average of all the current
Metal Transfer Regularity	Ar+CO2	Short Circuit	Regularity index $IVcc = \frac{\sigma_{tcc}}{tcc} + \frac{\sigma_{tab}}{tab} \quad (6)$  Cutting frequency index $Fcc = \frac{Valim \cdot (d)^2}{(k \cdot d)^3} \quad (7)$	$\sigma_{tcc}$ = standard deviation of the short-circuit time; $\sigma_{tab}$ = standard deviation of open arc time, $tcc$ = average of the short-circuit time; $tab$ = average open arc time. $d$ = wire-electrode diameter; $Valim$ = wire feed rate; $k$ = constant to estimate the drop diameter

**Table 1.**  
*Summary of arc stability indexes.*

formulation are presented in **Table 1**. They also use the voltage waveform to predict the mode of metal transfer because more variations are observed in the voltage moving from spray to short-circuit transfer. They perform a generalization and propose a new index power ratio (PR) (Eq. 5, **Table 1**), used for identification of the metal transfer mode and arc stability. Finally, an online monitoring system was created capable of predicting the status of the process.

Simpson [15] presents a stability index using an image processing method known as signature images. This index is calculated successively from the comparison of two images of dimensional histograms of the voltage and current data, allowing the detection of faults for the three main modes of metal transfer. Although it is a method of image processing which does not require high-speed cameras, instead, it is necessary for a good data acquisition system to work in real-time. Therefore, it can be considered as a cheap and feasible method to implement in the industry.

Finally, the group Laprosolda of the Federal University of Uberlândia, Brazil [12, 13, 16, 17], in a similar approximation, based on numerical and statistical techniques, propose two indexes for the short-circuit transfer mode: the regularity index (IVcc) (Eq. 6, **Table 1**) criteria for quantifying the short-circuit transfer stability in the MIG/MAG welding process, taking into account the constancy of the short-circuit and open-arc times, and cutting frequency index ( $\Delta Fcc$ ) (Eq. 7, **Table 1**) criteria to determinate the voltage regulation range that guarantees greater stability of metal transfer in GMAW short circuit. Using the parameters wire-electrode diameter, wire feed rate and drop diameter as a function of the wire diameter, they address metal transfer behavior (especially regarding the correlation between the stability of transfer mode and the welding defects). The use of these indices allowed the authors to test the correlation between the inductance; the regularity of the metallic transfer; and the influence of the variation in the contact tip to work distance (CTWD), with three different types of gases. In addition, the proposed indices have been widely used in other studies; some of them are discussed below.

Souza [18] presents a work related to mapping the droplet transfer modes to help welders in the choice of the best welding setting parameters needed. The maps were proposed for spray and short-circuit transfer modes. They used the  $IV_{cc}$  and  $\Delta F_{cc}$  parameters to allow focusing voltage range and to obtain transfer regions with proper operating characteristics for the short-circuit mode. The study demonstrates that the index has the characteristic of decreasing and then again increasing its value with increasing welding voltage. As smaller index values indicate better stability, it appears that the process has poor stability at very low and very high voltages.

Meneses [3] presents an implementation of a model that represents the GMAW process in orbital welding. She also developed a study of the metal transfer control, with the objective of achieving a high level of quality of welded joint in different conditions. The mentioned indices were used to make evaluating the hypothesis possible so that more short circuits had greater stability in the process. That allows users to choose a correct parameter setting depending on their needs, in order to obtain a stable transfer with appropriate welding conditions.

Costa [19] performed the validation of the stability on the welding process for the short-circuit transfer mode. The regularity index ( $IV_{cc}$ ) and cutting frequency ( $F_{cc}$ ) index were used, and this was able to identify the tension levels that result in greater transfer regularity, lower level of spatter, higher deposition efficiency, and better surface quality of the weld bead. In the next step, they used the deposition performance and allowed to estimate the amount of material lost by slag and fumes, along with the amount of generated spatter. It was also able to evaluate the effects of the feed rate and the influence of the type of protection gas on the behavior of short circuits. Finally, he developed a thermal efficiency analysis where he concludes that there is no relationship between the values of thermal efficiency and the regularity of transfer.

In conclusion, those indices are powerful tools to determinate the stability in the GMAW process and can be monitored in real time. The short-circuit frequency is one of the most suitable parameters to determine stability in the short-circuit transference mode, either by correlating it with the oscillation frequency of the weld pool or by calculating its standard deviation. The so-called Vilarinho index developed by the group Laprosolda has been widely adopted in Brazil, and it is the index of stability for short-circuit transfer of which the largest number of references was found.

### 2.3.3 Analysis of current and voltages waveforms

The analysis of current and voltage waveforms is used in the same way as an indicator of stability. Power spectral density and time-frequency analysis methods were used and allowed the decomposition in time and frequency of the waveforms.

Adolfsson and Bahrami [10] used spectral domain analysis of measurement data to detect differences in the power spectral densities of the weld voltage and current in disturbance moments. It made the creation of an algorithm that detects changes in the frequencies and that enables the detection of faults possible. They also affirm that a decrease in the variance was reflected in a decrease in the area in the power spectral density. This work was discussed previously in Section 2.3.1.

Also, Huang et al. [20] used time-frequency entropy techniques to estimate the stability of short-circuiting gas metal arc welding, demonstrating that when the welding is more stable, the time-frequency entropy increases. To obtain the results, the authors made variations in the input variables such as current, voltage, and welding speed, demonstrating that it is possible to use this technique to define the parameters that provide more stability. Finally, the results can be used to perform

the process classification in a stable and non-stable arc. It would be interesting in future works to get an integration of these techniques with supervised machine learning algorithms to perform stability classification.

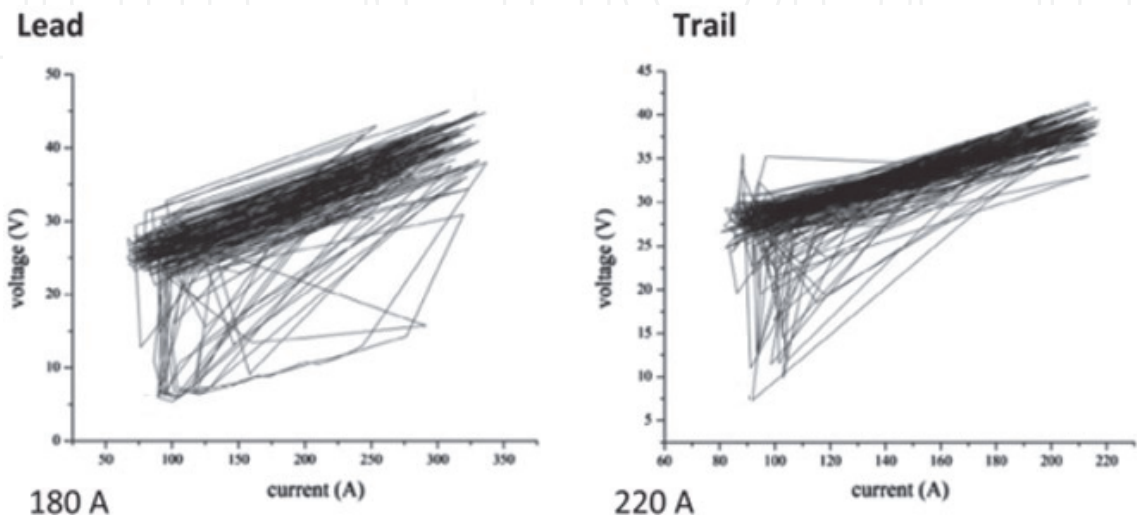
Chu et al. [21] perform an analysis of power spectral density of the current and voltage signals also for processes with short-circuit transfer mode using Fourier transformation to do that. To determine if the testing processes were stable, a correlation was made between the weld bead geometry and the voltage and current values. They affirm that the welding process with a unique frequency corresponds to uniform welds and good weld surface quality, enabling the detection of stable ranges and areas with defects.

Cayo and Alfaro [22] make a comparison between time domain and frequency domain to define which is most appropriate to calculate the stability of the S-GMAW welding process. Applying the two methods to the welding arc sound, the time domain was found to be the most appropriate technique. They also demonstrate that the acoustical ignitions frequency and short-circuit frequency decrease in regions of instability. The results obtained can be used for the development of an online system to identify regions of disturbances.

Macías et al. [23] use image processing to analyze the image generated by the time-frequency diagram obtained from acoustic monitoring. Proving that the minimum standard deviation of the metal transfer weld indicates that the process is stable, as previously mentioned. The authors did not implement online monitoring but highlight the existing flexibility in terms of image processing and online signal processing. It should be noted that in future works, the authors integrate their results into a neural network with artificial intelligence to predict stability in the process.

Then, it can be concluded that power spectral density is a powerful method for the quantification of stability and allows to identify faults in the process through the detection of changes in the waveform frequency. Then, it can be concluded that power spectral density is a powerful method for the quantification of stability and allows to identify faults in the process through the detection of changes in the waveform frequency, being possible to correlate with the quality of the geometry of the weld bead.

The current and voltage signals have also been used to create cyclograms that show the welding voltage as a function of welding current to obtain a process stability indicator. Cyclograms are a novel method for stability analysis in the welding process. They constitute a visual representation by graphs of the voltage values as a function of the current (**Figure 9**). It has been widely used as a stability indicator for the short-circuit transfer mode.



**Figure 9.**  
*Representation of the cyclograms (modified from [24]).*

According to Moinuddin and Sharma [24], using the cyclograms it is possible to represent characteristics of droplet detachment and arc burning stage. The authors also carried out an analysis of probability density distribution of arc voltage, weld bead, and microstructure analysis for various welding conditions, allowing to extend the stability study to spray transfer mode. The study showed that there is a strong correlation between the microstructure and the stability of the arc. Besides, the different types of electrodes and their electrical conductivity capacity also has influence on the resulting microstructure in a welded bead. A stable arc produces greater penetration and improves melting efficiency. The authors mention that the study can be expanded taking into account other parameters such as electrode type, electrode extension, shield protection gas, welding speed, and other current modes such as pulsed.

Cayo [25] uses the cyclograms to detect defects in the weld reflected in the arc and current–voltage signals. The cyclograms allowed to identify three types of disturbances, a variation of the stand of, presence of grease and absence of protection gas. Each type of defect showed changes in the cyclograms, allowing to analyze the changes in voltage and current. One of the advantages of the cyclograms is that it provides a visual result that allows a quick analysis of the values obtained in the process. Again a powerful stability indicator is shown, but it has been oriented only to the analysis of the short-circuit transfer mode.

Suban [26] uses this index to determine a more stable short-circuit material transfer. As a result, open arc, short-circuit, and spray transfer moments are identified depending on the type of gas used. In addition, the author performs an analysis of the probability distribution of voltage and current using Fourier analysis. Among the conclusions, the authors emphasize that with pure CO<sub>2</sub>, more stability is achieved. This method is simple and can be implemented in real time.

#### 2.3.4 Control of droplet size

The control of droplet size ensures transfer stability. For measuring this variable, image processing, laser shadowing, and sound processing techniques are generally used. The appropriate control ensures proper transfer mode; increases the quality of welding, and decreases the number of defects. Large drops do not represent a suitable condition.

The transfer of the drop is dependent on welding current and arc voltage waveforms influenced by gravity force, electromagnetic force, plasma drag force, and surface tension. Suban [26] ensures that to maximize stability, the time between the transfers of two subsequent drops should always be the same.

Mousavi and Kulkarni [27, 28] demonstrate that a relationship between droplet detachment and statistical parameters of current exists, assuring that lesser standard deviation and coefficient to variation was considered to be of uniform droplet detachment and arc length uniformity.

Soderstrom and Mendez [29] use high-speed laser shadowgraphs and fast Fourier transform (FFT) of the voltage signal for droplet diameter and detachment frequency measurement. It has been found that a relationship between average droplet diameter and current for the different diameter electrodes exists. In addition, it states that the increase in CO<sub>2</sub> above normal standards causes an erratic detachment.

Then it can be concluded that there is a correlation between the waveform of the current and the detachment of the drop. A lower coefficient of variation in the mean of the welding current represents uniformity in the detachment frequency. Additionally, for variable transfer time, the welding arc tends to be unstable and the current signals exhibit irregular behavior. In the case of short-circuit transfer mode,

it is recommended to detach one dropper short. Equally Pal et al. [30] affirm that in the pulsed welding processes, the detachment of the drop should occur during the pulses and the diameter of the drop should be similar to the diameter of the electrode. Finally, adequate control and study of the metallic transfer allow guaranteeing the quality in the geometry of the welded bead.

2.3.5 Spattering index

The amount of spatters generated during the welding process has been another indicator widely used; the spatters are a product of instability in the arc and should be minimized. The largest amount of study is developed in the short-circuit area. The moment when the short circuit occurs and the arc is reset is when the largest number of spatters is produced. Also, if the mean of the short-circuit time is irregular, more spatters will be generated.

Silva et al. [31] propose a criterion for the spattering index correlating spattering rate (S—Eq. 1, **Table 2**) and the deposition rate (D—Eq. 2, **Table 1**). The purpose was to demonstrate that the correct control of these indicators allows to choose appropriate parameters for any specific welding application.

On the other hand, Kang and Rhee [32] develop statistical regression models to predict the amount of spatter in the short-circuit transfer for GMAW. It is shown, in the same way, that voltage and welding current waveforms can be satisfactorily used to predict the presence of spatters. Kang et al. [33] in a similar work use four different linear and nonlinear regression models composed of the waveform factors to develop the spatter prediction model. Proving that the amount of spatter depends on the number of arc extinctions, arc extinctions occur when the welding voltage is

Objective	gas	Transfer mode	Equation	Measured parameters and Variables
Calculate Spattering Index	CO2	Globular Spray Short Circuit	spattering index $SI = \frac{S}{D} * 100 \quad (\%) \quad (1)$ spattering rate $S = (F_{elect} \text{ or } F_{wire}) - D. \quad (2)$ Deposition rate $D = 3,6 \times (M_{fcp} - M_{icp}) / t_{arc} \quad (3)$ Covered electrode fusion rate $F_{elect} = 3,6 \times (M_{iel} - M_{fel}) / t_{arc} \quad (4)$  Penetration index $PI = (p / t) \times 100 \quad [\%]. \quad (5)$ The convexity index $CI = (r / w) \times 100 \quad [\%]. \quad (6)$	The penetration index (PI) was defined by relating the depth of the weld bead (P) to the sheet thickness (t). CI was defined as a relationship between the bead reinforcement (r) and the bead width (w), in percentage, where p is the weld penetration [mm], t is the joint thickness [mm], r is the bead reinforcement [mm], w is the bead width [mm], S is the spattering rate [kg/h], D is the deposition rate [kg/h], F <sub>elect</sub> is the covered electrode fusion rate [kg/h], M <sub>iel</sub> is the initial mass of the covered electrode, before welding [g], M <sub>fel</sub> is the final mass of the covered electrode, after welding [g], t <sub>arc</sub> is the arc duration time [s], F <sub>wire</sub> is the wire fusion rate [kg/h], ϕ is the wire diameter [mm], f <sub>wire</sub> is the wire feed rate [m/min], γ is the steel density (7.85 x 103 g/mm3), M <sub>fcp</sub> is the final mass of the test plate, after welding [g], M <sub>icp</sub> is the initial mass of the test plate, before welding [g] and de is the deposition efficiency [%].
Calculate Spatter Index Stability Index	CO2	Short Circuit	Spatter Index $F_{sp} = \frac{W_{sp}}{W_{sp} + W_{bead}} * 100 \quad (7)$  Index of stability (SI) was defined as: $SI = \frac{K}{F_{sp}} \quad (8)$	W <sub>sp</sub> is the weight of the spatter collected in the box, and W <sub>bead</sub> is the weight of the weld bead.  Where K is an arbitrary constant, which was considered by the author be equal to 100

Table 2.  
Summary of transfer stability indexes.

below the optimum. In another study, models were developed for evaluating the spatter rate based on the conventional feed-forward multilayer perceptrons with the error back-propagation as the learning algorithm to estimated spatter rate.

Lastly, Fernandes et al. [34] propose a spatter index (Eq. 7, **Table 2**) relating in a mathematical equation of the weight of the spatter collected in the box and weight of the weld bead. Using the calculated value of the spatter index, they propose a new index of stability (Eq. 8, **Table 1**) that enhances the electrical stability of the process and the weight of spatter generated during welding. The proposed method is efficient as soon as the collection of spatters is carried out correctly. It is suitable for a laboratory environment but can hardly be implemented in the industry since it depends on the collection device. However, the results obtained can be generalized in an automatic learning model and implemented for the control of spatters.

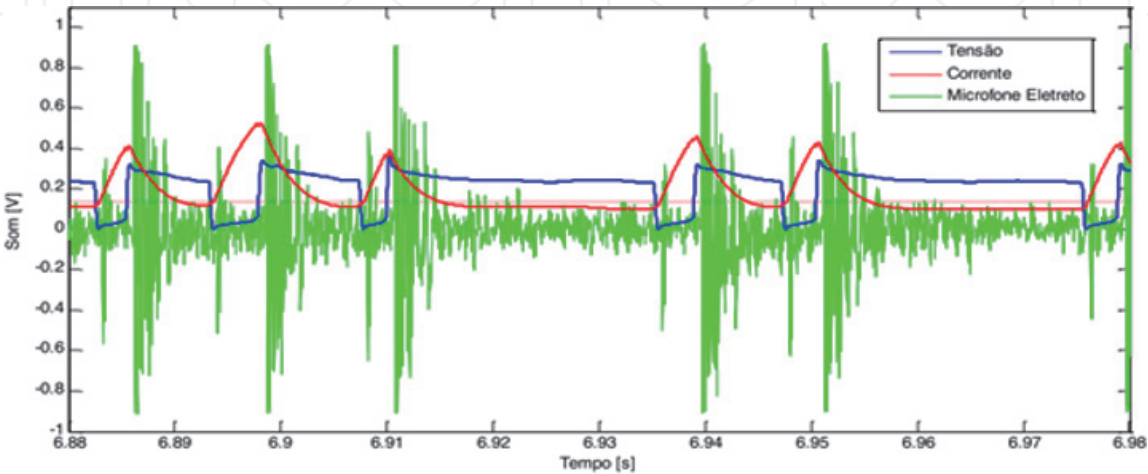
2.3.6 Acoustic monitoring

According to Grad et al. [35], the acoustic signal contains information about the transfer mode and the behavior of the arc. It is also possible to identify changes in arc dimensions and geometry; changes in arc intensity; and metal transfer and oscillations of the molten pool.

Even according to Mota et al. [36], it is possible to observe that the sound signal accompanies the electrical signal, specifically the voltage, in relation to the moments of extinction and ignition of the arc. It is easy to see in **Figure 10** the sound pulses from the moments of the abrupt change in the voltage of the electric arc, and the time intervals between them follow the same pattern observed in the electric signal.

Grum et al. [37] use the sound signal and the light signal to detect even the smallest deviations of arc behavior, as well as large deviations due to the material transfer mode and excessive/inadequate weld penetration. They propose a mathematical model using sound and light values. The authors demonstrated the existence of a correlation between light signals and the energy provided to the system. With the monitoring of sound, it was possible to identify oscillations in the arc that indicated instability. The model was developed for the short-circuit transfer mode but was generalized for the spray transfer mode.

Cayo and Alfaro [38] use the sound to define the difference between the transfer modes on the GMAW process. They use sound pressure and current signals to identify changes in the transfer mode and identify defects. In the case of the spray



**Figure 10.**  
*Comparison between sound and current signals (modified from [36]).*

transfer mode, the drops are small and practically imperceptible during the acoustic analysis. Already in the case of the short circuit, it is possible to monitor the occurrence of each short and the reignition of the arc.

Roca et al. [39] also applied acoustic monitoring, and the results obtained were used for the training of a neural network. To perform the analysis, they obtain the standard deviations of the peak amplitudes of the sound at the moment in which the short circuit is made, and they use as stability indicator. In Eq. 12, **Table 1** shows the stability index previously established. The combination of statistical technique, acoustic monitoring, and artificial intelligence allowed to use online monitoring, considering it an efficient and non-destructive technique.

It can be summarized that the electrical and acoustic signals are correlated mainly in the short-circuit transfer mode where it is possible to identify the detachment of the drop and the arc reignition. In addition, it is possible through sound monitoring to identify the transference modes. It is a method that is not expensive and that is feasible to implement in the industry. The combination of this method with machine learning techniques that allow prediction and classification is open for future works.

3. Synthesis of the study and future research directions

To synthesize the study, an analysis of the documentation was obtained, the metadata of the document collection was exported in Information Systems Research (RIS) format, and a bibliometric analysis was performed using the VOSViewer software. A graph with groups of the main authors and their relationship of co-authorship (taking five as a frequency of occurrence of the author's surname) is presented in **Figure 11**. It is possible to identify as the largest cluster the Chinese authors, followed by smaller groups of Brazilian and Indian authors, highlighting that there is little cooperation between those groups.

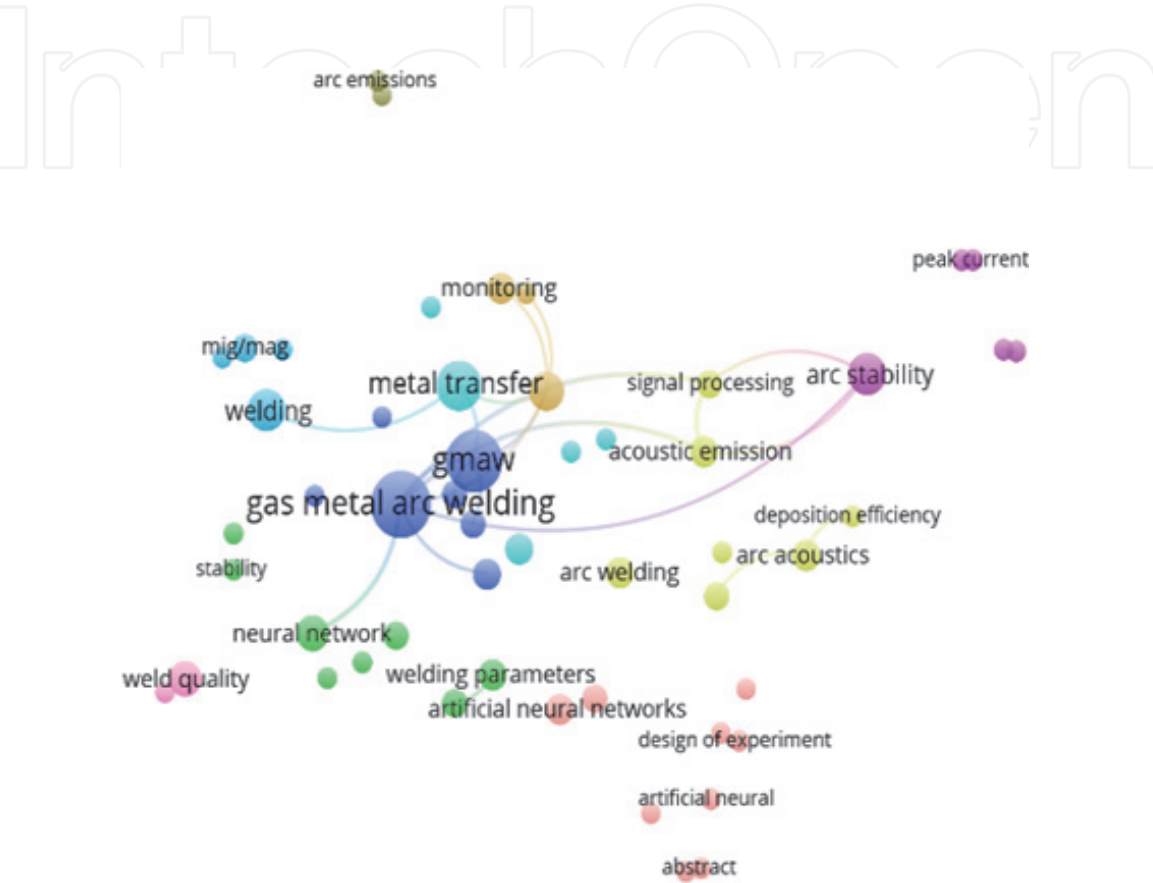
**Figure 12** shows the most used terms in the area that can be defined as keywords.



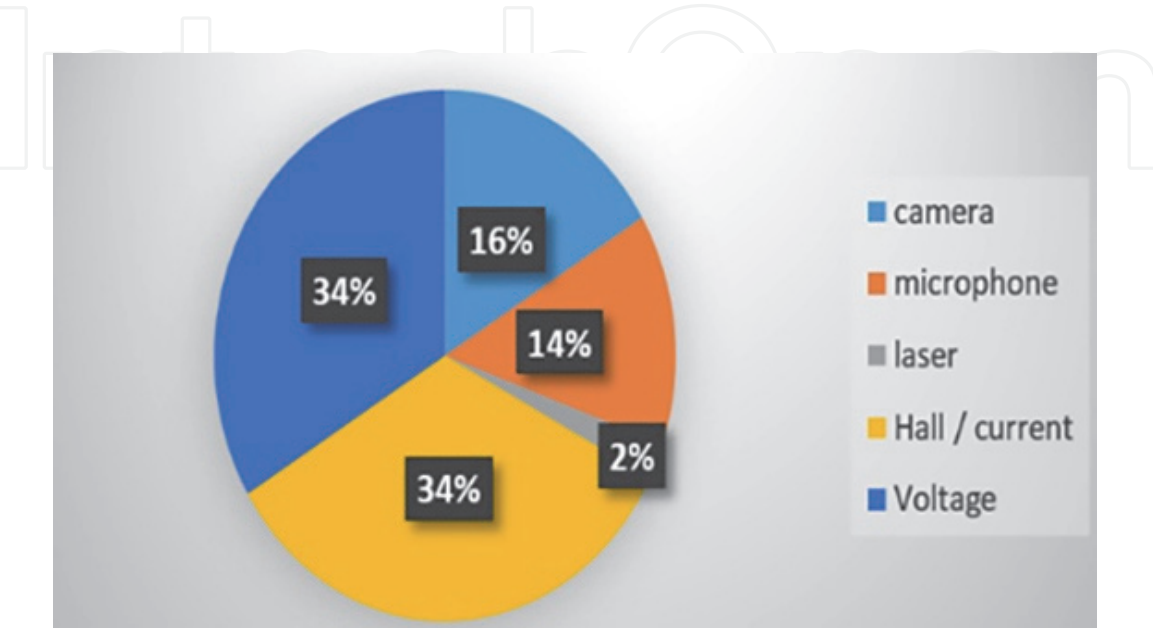
**Figure 11.**  
*Authors and their relationship of co-authorship (two as a frequency of occurrence of the author's surname).*

**Figures 13 and 14** show a summary of the signals and methods used to measure or estimate the indexes. Consequently, the current and voltage signals are widely used, as well as the camera in the image processing and the microphone for the analysis of acoustic signals.

**Figure 15** summarizes the parameters and variables used in the studies showing that among the most influential in the stability of the process, current, voltage, wire feed speed, short-circuit time, arcing time, and short-circuit frequency can be mentioned.

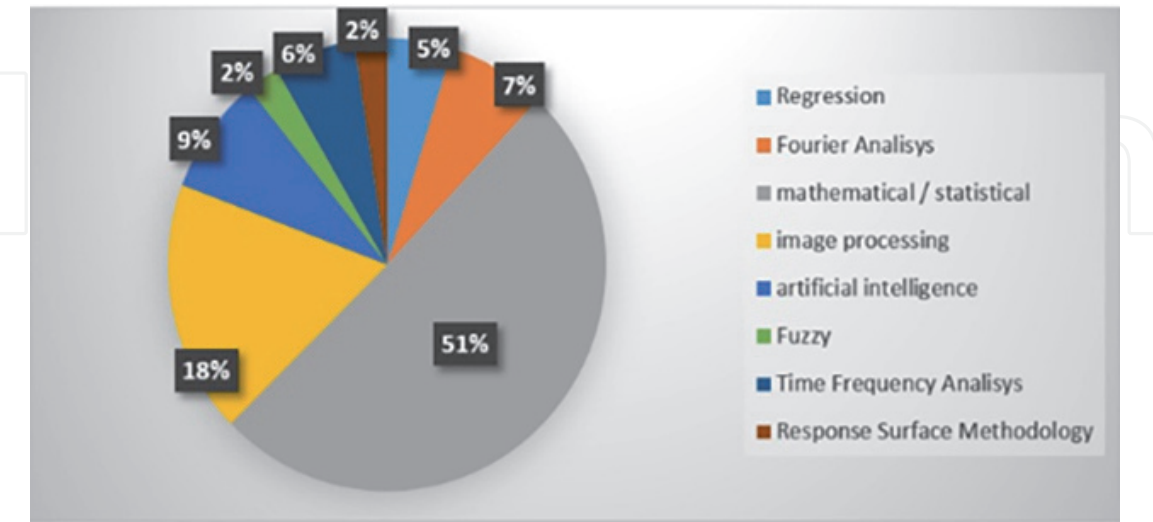


**Figure 12.**  
*Cluster of terms (two as a frequency of occurrence of the term).*

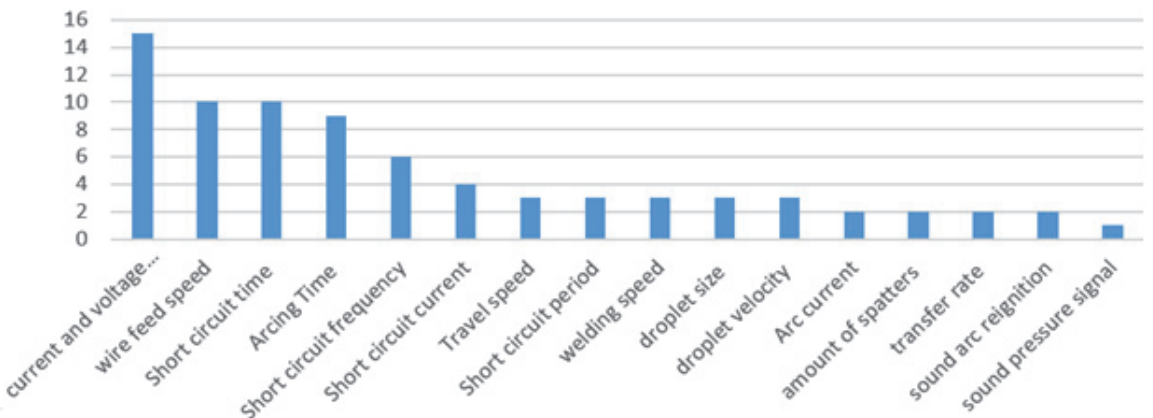


**Figure 13.**  
*Sensors used to measure.*

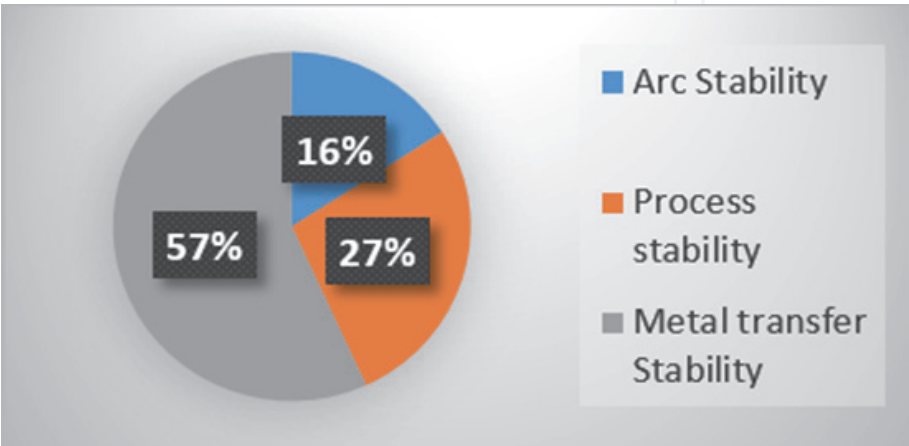
Also, it is possible to classify the indexes into groups according to their purpose, those that are oriented to the monitoring of the metallic transfer, and the analysis of the stability of the arc and the process in general. **Figure 16** shows the percentage by group; **Figure 17** shows the technique used to develop the indexes for those groups. It is important to emphasize that these concepts are widely correlated.



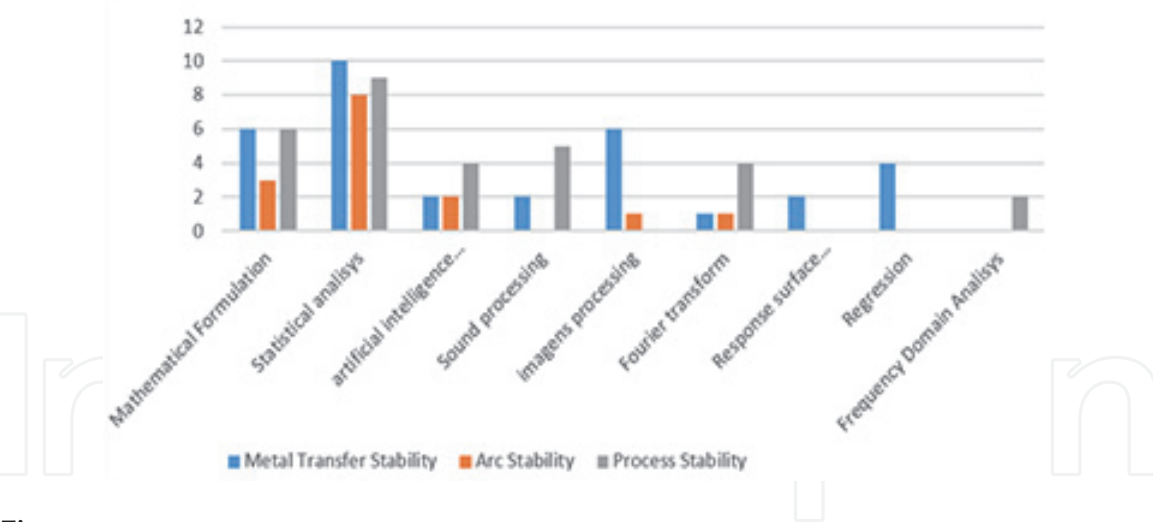
**Figure 14.**  
*Methods used to estimate the indexes.*



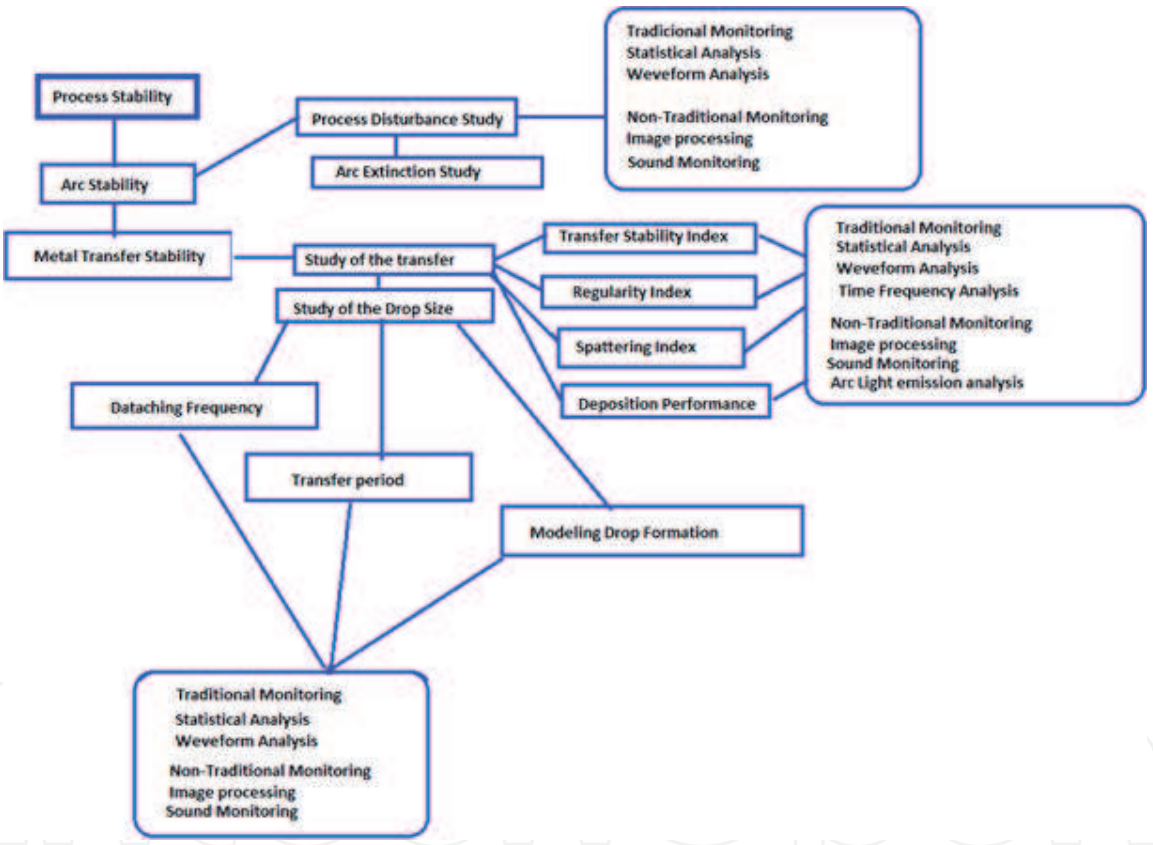
**Figure 15.**  
*Parameters and variables used in the studies.*



**Figure 16.**  
*Percentage by group.*



**Figure 17.**  
*Techniques used to develop the indexes classified by groups.*



**Figure 18.**  
*Classification of the main methods used for monitoring.*

Note that the highest percentage of investigation is aimed at the study of metal transfer stability. It is also evident that the main processing techniques to develop the indexes were the mathematical formulation and statistical methods. Although in the case of metal transfer, image processing is widely used, mainly to define the transfer mode and drop size.

**Figure 18** shows a taxonomy that details the methods used to measure the stability of the welding process and the techniques associated with them. The techniques used were divided according to Weglowski [40] into traditional and nontraditional.

Finally, to find a trend and a possible vision of the direction of future studies, the following was analyzed:

### 3.1 Highlights of the works of the last 5 years

An analysis of the works in the field of stability in the last 5 years was made and allowed to find the following trends. There is a considerable increase in the study and application of works in pulsed GMAW (**Figure 19**). This increase is caused by the known improvements in quality and productivity with respect to regular metal gas arc welding (GMAW).

Another trend that could be identified is the increase in research that integrates classical statistics techniques and novel machine learning algorithms. It is well known that with the increase of the computing processing capacities, the data analysis, big data, and machine learning have had a significant boom since 2009. The welding area has not been oblivious to the use of such techniques, although it should be noted that in the area of stability, classical statistics is more commonly used as demonstrated in the present study.

Already in recent years, some interesting solutions have been presented. Alizadeh and Omrani [41] integrate successfully the Taguchi method with back-propagation neural network (BPNN) technique for controlling quality in offline mode. Gyasi et al. [42] are employing an artificial neural network (ANN) to predict geometric characteristics of the welded cord. Wan et al. [43] integrate multiple linear regression analysis and back-propagation neural network to estimate the weld quality. Yue-zhou et al. [44] use sound monitoring and develop a classification algorithm with SVM (support vector machine). Sumesh et al. [45] use machine learning algorithms for weld quality monitoring, acoustic signature, and the perform classification use J48 and random forest algorithms.

In addition, there has been an increase in the use of artificial intelligence algorithms and sensorial fusion. Two powerful techniques have enabled the monitoring and control of welding processes in real time. Also, and as expected, we already find in the literature novel proposals for applications of artificial intelligence and robotics.

Another area that has been highly developed in recent years and future perspectives is image processing. A great number of algorithms have been created for high performance in this subject. Thanks to these advances, the monitoring of the weld bead in real time is now a reality.

### 3.2 Innovative techniques

It is known that metal transfer has a direct influence on the stability of the process and on the final quality of the welding. Consequently, it has been widely studied as demonstrated in the present review of the literature.

But innovative techniques continue to appear in this field with future prospects of great interest. In this case, they were identified as laser-enhanced gas metal arc welding (GMAW), a modification of GMAW, used to control the metallic



**Figure 19.**  
*Number of publications for years in the area of pulsed GMAW.*

transfer. A low power laser helps to obtain greater strength in the detachment of the drop. It was also determined as a newly developed arc welding method and ultrasonic-wave-assisted arc welding. This new technique uses power ultrasound energy to radiate the arc and weld pool, modifying the speed with which the plasma heats and cools. According to Fan et al. [46], it allows increasing the stability of the process.

### **3.3 Areas where further study is required**

Very correlated with the study of acoustic monitoring is the analysis of the arc light emission. It is used to control the metallic transfer. A low power laser helps to obtain greater strength in the detachment of the drop. Weglowski [47] demonstrate that light emission has a linear correlation with the current. By another hand, Shao et al. [48] affirm that the light signal indicates the arc radiation intensity and the arc radiation is proportional to the power released which has been a relevant indicator of the energy supplied into the weld.

To a lesser extent and with little representation in the scientific literature, there are works related to the quantification of the emission of fumes. Yamamoto et al. [49] conclude that a relation between heat content, fume emission rate, and molten metal transfer mode exists; consequently the fume emission rate per unit weight of consumed wire increases with the increase in heat content.

But Meneses et al. [50] proved that there is no correlation between the amount of spattering generated and fume generation rate, because the regularity of the transfer did not show influence on the morphology, size or composition of the fumes. Then the generation of fumes is not correlated with the stability of the process.

Finally, other techniques that can be developed are 3D computational modeling, simulation, spectroscopy, spectral analysis, and X-ray observation system.

## **4. Conclusions**

- The chapter shows reliable and precise methods to measure the stability in the GMAW welding process.
- The greatest amount of effort in the area has been directed towards the study of metallic transfer.
- The transfer mode for which most indexes have been created is the short circuit.
- The indexes have been developed through the analysis of process signals as current, voltage, sound, and light.
- Techniques such as mathematical formulation, statistical analysis, image processing, and monitoring of acoustic signals and light spectrum are mentioned among the most useful.
- The methods of artificial intelligence and machine learning have been little used leaving an interesting path to be traveled in future research.

## Acknowledgements

This work has been supported by the Brasilia University (UnB), the government research CAPES foundation and CNPQ.

## Conflict of interest

Elina Mylen Montero Puñales and Sadek Crisóstomo Absi Alfaro declare that they have no conflict of interest.

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## References

- [1] Wu C, Polte T, Rehfeldt D. A fuzzy logic system for process monitoring and quality evaluation in GMAW. *Welding Journal*. 2001;**80**:33-38
- [2] Ponomarev A. Arc Welding Process Statistical Analysis. Methodical Approaches, Analysis Conceptions, Experiences. Denmark: DTU-Helsingor, JOM-Institut.; 1997. pp. 59-100
- [3] Meneses LYH. Modelagem E Simulação Da Transferência Metálica No Processo Gmaw-S Em Soldagem Orbital. Brasília: UNB; 2013 p. 196
- [4] Pinto Lopera JE. Uso de agentes inteligentes no controle simultâneo da largura e do reforço dos cordões de solda no processo GMAW-S. 2016
- [5] Margarita E et al. Parameter Optimization in Gmaw Process With Solid and Metal-Cored Wires. Uberlandia, Brasil: Cobem, ABCM; 2013. pp. 5256-5266
- [6] Bestard GA. Sensor Fusion and Embedded Devices to Estimate and Control the Depth and Width of the Weld Bead in Real Time. Brazil: Universidade de Brasília-UnB; 2017
- [7] De Figueiredo KM. Mapeamento dos Modos de Transferência Metálica na Soldagem Mig de Alumínio. Brazil: Universidade Federal de Uberlândia; 2000
- [8] Chávez JJM. Uma Metodologia Para Obtenção E Validação De Parâmetros Ótimos Em Soldagem Gmaw Pulsado. Brazil: UNB; 2014. p. 190
- [9] Mita, Sakabe, Yokoo. Quantitative estimates of arc stability for CO<sub>2</sub> gas shielded arc welding. *Welding International*. 1988;**2**(2):152-159
- [10] Adolfsson S, Bahrami A. On-line quality monitoring in short-circuit gas metal arc welding. *Welding Journal*. 1999;**78**(2):59S-73S
- [11] Luksa K. Influence of weld imperfection on short circuit GMA welding arc stability. *Journal of Materials Processing Technology*. 2006; **175**(1-3):285-290
- [12] Wu CS, Gao JQ, Hu JK. Real-time sensing and monitoring in robotic gas metal arc welding. *Measurement Science and Technology*. 2007;**18**(1): 303-310
- [13] Hermans M, Den Ouden G. Process behavior and stability in short circuit gas metal arc welding. *Welding Journal*. 1999;**78**:137-141
- [14] Ogunbiyi B, Norrish J. Monitoring indices for metal transfer in the GMAW process. *Science and Technology of Welding and Joining*. 1997;**2**(1):33-35
- [15] Simpson SW. Signature image stability and metal transfer in gas metal arc welding. *Science and Technology of Welding and Joining*. 2008;**13**(2): 176-183
- [16] Modenesi RCAPJ. The influence of small variations of wire characteristics on gas metal arc welding process stability. *Journal of Materials Processing Technology*. 1997;**86**:226-232
- [17] de Rezende GMC, Liskévych O, Vilarinho LO, Scotti A. Um critério para determinar a regulação da tensão em soldagem MIG/MAG por curto-circuito. *Soldagem & Inspeção*. 2011;**16**(2):98-103
- [18] Souza D. Levantamento de Mapas Operacionais de Transferência Metálica para Soldagem MIG/MAG de Aço ao Carbono na Posição Plana. Brazil: Universidade Federal De Uberlândia; 2010
- [19] Costa TF. Avaliação De Critérios De Estabilidade Do Processo Mig/Mag

Curto-Circuito Na Soldagem De Aços Inoxidáveis Austenítico E Duplex. Brazil: Universidade Federal De Uberlândia; 2014

[20] Huang Y, Wang K, Zhou Z, Zhou X, Fang J. Stability evaluation of short-circuiting gas metal arc welding based on ensemble empirical mode decomposition. *Measurement Science and Technology*. 2017;**28**(3):12

[21] Chu SPMYX, Hu SJ, Hou WK, Wang PC. Signature analysis for quality monitoring in short-circuit GMAW. *Welding Journal*. 2004;**83**(12):336S-343S (December)

[22] Cayo EH, Alfaro SCA. A non-intrusive GMA welding process quality monitoring system using acoustic sensing. *Sensors (Basel)*. 2009;**9**(9): 7150-7166

[23] Macías EJ, Roca AS, Fals HC, Fernández JB, de la Parte MP. Time-frequency diagram applied to stability analysis in gas metal arc welding based on acoustic emission. *Science and Technology of Welding and Joining*. 2010;**15**(3):226-232

[24] Moinuddin SQ, Sharma A. Arc stability and its impact on weld properties and microstructure in anti-phase synchronised synergic-pulsed twin-wire gas metal arc welding. *Materials and Design*. 2015;**67**: 293-302

[25] Cayo E. Weld transference modes identification through sound pressure level in GMAW process. *Journal of Achievements in Materials and Manufacturing Engineering*. 2008; **29**(1):57-62

[26] Suban M. Determination of stability of MIG/MAG welding processes. *Quality and Reliability Engineering International*. 2001;**17**(5):345-353

[27] Mousavi M, Haeri M. Welding current and arc voltage control in a

GMAW process using ARMarkov based MPC. *Control Engineering Practice*. 2011;**19**(12):1408-1422

[28] Kulkarni SD, Mallya UD, Chaturvedi RC. Droplet detachment and plate fusion characteristics in pulsed current gas metal arc welding. *Welding Journal*. 1998;**6**(June):254-269

[29] Soderstrom EJ, Mendez PF. Metal transfer during GMAW with thin electrodes and Ar-CO<sub>2</sub>. *Welding Research*. 2008;**87**(May):124-133

[30] Pal K, Pal SK. Effect of pulse parameters on weld quality in pulsed gas metal arc welding: A review. *Journal of Materials Engineering and Performance*. 2011;**20**(6):918-931

[31] Silva CR, Ferraresi VA, Scotti A. A quality and cost approach for welding process selection. *Journal of the Brazilian Society of Mechanical Sciences and Engineering*. 2000;**22**(3): 389-398

[32] Kang, Rhee. The statistical models for estimating the amount of spatter in the short circuit transfer mode of GMAW. *Welding Journal*. 2001;**80**:1-8

[33] Kang MJ, Kim Y, Ahn S, Rhee S. Spatter rate estimation in the short-circuit transfer region of GMAW. *Welding Journal*. 2003;**82**(9):238s-247s

[34] Fernandes DB, de Menezes Júnior LC, Vilarinho LO, Scotti A. Ensaio para medição de nível e alcance de respingos em soldagem MIG/MAG. *Soldag. e Insp.* 2010;**15**(2):150-151

[35] Grad L, Grum J, Polajnar I, Slabe JM. Feasibility study of acoustic signals for on-line monitoring in short circuit gas metal arc welding. *International Journal of Machine Tools and Manufacture*. 2004;**44**(5):555-561

[36] Mota CP, Mendes R, Neto F, Vilarinho LO. Do Por Curto-Circuito. 2013

- [37] Grum J, Bergant Z, Polajnar I. Monitoring the GMAW process by detection of welding current, light intensity and sound. In: Defectoscopy 2012, Czech Republic: Czech Society for Nondestructive Testing; 2012
- [38] Cayo, Alfaro. Welding Quality Measurement Based on Acoustic Sensing. Brazil: COBEM, ABCM; 2008
- [39] Roca AS, Fals HC, Fernández JB, Macías EJ, De La Parte MP. Artificial neural networks and acoustic emission applied to stability analysis in gas metal arc welding. *Science and Technology of Welding and Joining*. 2009;**14**(2):117-124
- [40] Węglowski M. Modeling and analysis of the arc light Spectrum in GMAW. *Welding Journal*. 2008;**87** (August):212-218
- [41] Alizadeh A, Omrani H. An integrated multi response Taguchi-neural network- robust data envelopment analysis model for CO<sub>2</sub> laser cutting. *Measurement*. 2019;**131**: 69-78
- [42] Gyasi EA, Kah P, Wu H, Kesse MA. Modeling of an artificial intelligence system to predict structural integrity in robotic GMAW of UHSS fillet welded joints. 2017;1139-1155
- [43] Wan X, Wang Y, Zhao D, Huang Y, Yin Z. Weld quality monitoring research in small scale resistance spot welding by dynamic resistance and neural network. *Measurement*. 2017;**99**:120-127
- [44] Ma YZ, Qu M, Chen JH. SVM classifier for wire extension monitoring using arc sound signal in GMAW. *Transactions of the China Welding Institution*. 2006;**27**(5):21-26
- [45] Sumesh A, Rameshkumar K, Mohandas K, Babu RS. Use of machine learning algorithms for weld quality monitoring using acoustic signature. *Procedia Computer Science*. 2015;**50**: 316-322
- [46] Fan C, Xie W, Yang C, Lin S, Fan Y. Process stability of ultrasonic-wave-assisted gas metal arc welding. *Metallurgical and Materials Transactions A: Physical Metallurgy and Materials Science*. 2017;**48**(10): 4615-4621
- [47] Węglowski MS, Huang Y, Zhang YM. Relationship between wire feed speed and metal transfer in GMAW. *Journal of Achievements in Materials and Manufacturing Engineering*. 2008;**29**(2):191-194
- [48] Shao Y, Wang Z, Zhang Y. Monitoring of liquid droplets in laser-enhanced GMAW. *International Journal of Advanced Manufacturing Technology*. 2011;**57**(1-4):203-214
- [49] Yamamoto E, Yamazaki K, Suzuki K, Koshiishi F. Effect of flux ratio in flux-cored wire on wire melting behaviour and fume emission rate. *Welding World*. 2013;**54**(5-6):R154-R159
- [50] De Meneses VA, Gomes JFP, Scotti A. The effect of metal transfer stability (spattering) on fume generation, morphology and composition in short-circuit MAG welding. *Journal of Materials Processing Technology*. 2014;**214**(7):1388-1397