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Acoustic analysis in gas metal arc welding: Physical mechanisms, signal processing, and applications

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ABSTRACT

Acoustic analysis has emerged as a promising, non-intrusive approach for process monitoring and quality assessment in gas metal arc welding (GMAW). The sound generated during the GMAW process originates from complex physical phenomena, including arc plasma dynamics, metal transfer mechanisms, weld pool oscillations, and shielding gas flow. Therefore, acoustic signal contains significant information related to process stability and weld formation. During the previous decades, numerous researches have been focused on the application of audible sound and acoustic emission for real-time monitoring of the GMAW process. This paper provides an overview of the application of acoustic analysis in the GMAW process. The basic mechanisms of acoustic signal generation, as well as signal acquisition and processing techniques in the time, frequency, and time-frequency domains, are considered. Key application areas are reviewed, including process stability monitoring, weld quality assessment, metal transfer mode classification, and welding defects detection. Special attention is paid to contemporary trends, challenges and the integration of acoustic analysis with intelligent welding systems, highlighting its potential as a supplementary tool for advanced GMAW process monitoring.

KEYWORDS

Gas metal arc welding, Acoustic analysis, Acoustic emission, Signal processing, Metal transfer modes, Process stability, Weld quality, Machine learning.

1. INTRODUCTION

Gas metal arc welding (GMAW) is one of the most commonly applied arc welding processes in the modern manufacturing industry, thanks to its high productivity, convenience for automation, and the possibility of welding a wide range of materials and thicknesses. However, the quality and stability of the GMAW process largely depend on complex and extremely dynamic phenomena, such as the behavior of the electric arc, metal transfer mechanisms, dynamics of the molten pool, as well as the mutual interactions of electrical, thermal, and mechanical effects. Changes in these phenomena can lead to the occurrence of various welding defects, including lack of fusion, porosity, excessive spatter, burn-through, and inconsistent penetration, which directly affect the mechanical properties and reliability of welded joints [1-5].

Traditionally, the monitoring and control of the GMAW process have been based primarily on the analysis of electrical signals, such as welding current and voltage, as well as optical measurement methods and non-destructive testing (NDT) techniques applied after the process is completed. Although these methods provide valuable information about welding flow and joint quality, they often have significant limitations, including sensitivity to intense arc radiation and fumes, high complexity of measurement systems, and delayed error detection. These limitations have been documented in numerous studies dealing with welding process monitoring and multi-sensor approaches [6,7]. For this reason, in recent years, there has been a growing interest in alternative sensor approaches that enable the monitoring of processes in real time, in a non-intrusive and economically profitable manner.

Among these approaches, acoustic analysis stood out as a promising tool for monitoring and diagnosing the welding process. Sound generated during the GMAW process originates from multiple physical sources, primarily associated with arc plasma fluctuations, metal transfer events, and fluid-electromagnetic interactions. As a consequence, the acoustic signal inherently contains information about the stability of the process, the mode of metal transfer, and the quality of the welded joint [8-12]. In addition to physically measurable acoustic characteristics, psychoacoustic research has shown that experienced operators can subjectively assess welding stability based solely on sound perception, which further confirms the information richness of acoustic emissions in the GMAW process [13,14].

The application of acoustic emission in welding can be traced back to the pioneering work of Jolly [15,16], who showed that acoustic emission signals can be used to detect crack initiation, porosity, and inclusions in real time, during the welding process itself and subsequent cooling of the weld metal. One of the first systematic studies of acoustic emission signals in welded joints further demonstrated that acoustic emission signals activity is strongly related to the occurrence of defects and structural changes occurring during welding [17]. Early experimental research also confirmed that acoustic emission signals during welding is closely related to transient metallurgical processes and defect formation mechanisms, thus confirming the feasibility of applying acoustic emission signals methods for process monitoring directly during welding [18].

This early research pointed to one of the key advantages of acoustic monitoring compared to conventional NDT methods, which is the ability to obtain real-time process information. This enables earlier identification of defect mechanisms and reduces the need for subsequent inspection of welded joints and corrective actions after welding [15], [19-21]. Subsequent studies further confirmed the applicability of acoustic emission signals diagnostics for identifying the lack of fusion and other irregularities in welded joints in industrial conditions [3].

After these initial investigations, numerous works have dealt with the application of audible sound and acoustic emission signals for online monitoring of the GMAW process. Research has shown that acoustic characteristics extracted in the time, frequency, and time-frequency domains can be effectively related to welding stability, short circuit behavior, and metal transfer dynamics [22-25]. In particular, different metal transfer modes, such as short-circuit, globular, spray, and pulsed GMAW, have been shown to possess characteristic acoustic signatures, enabling reliable classification of transfer modes based on sound analysis [11,12], [26-28].

In addition to process stability assessment and metal transfer mode identification, acoustic measurement was also applied to weld quality assessment and defect detection. Successful examples of burn-through detection, lack of fusion, porosity, and penetration variations using acoustic characteristics in combination with statistical analysis, regression models, and machine learning methods (ML) have been recorded in the literature [1-5]. Recent works have further improved these approaches by introducing advanced methods of signal processing, sensor fusion, and artificial intelligence, including neural networks and deep learning, thus increasing the robustness and accuracy of prediction in industrial settings [29-32]. A comprehensive review of acoustic emission signals techniques for the evaluation of welded structures and their structural reliability is provided by Nedoseka [20].

In parallel with experimental research, efforts were made to improve the physical understanding of sound generation mechanisms in the GMAW process. Analytical and numerical models describing the dynamics of metal transfer and arc behavior have provided a deeper insight into the relationship between droplet motion, electromagnetic forces and acoustic emission signals [27,28],[33-35]. Recently, models with lumped parameters have been proposed, as well as numerical models that explicitly consider the generation of sound in the GMAW process, which further strengthens the theoretical basis of acoustic monitoring [35]. However, despite extensive experimental research, the physical modeling of sound generation in the GMAW process is still fragmentary and incomplete, which limits the predictive capabilities of acoustic analysis.

Despite significant progress made over the last few decades, the application of acoustic analysis in the GMAW process still faces challenges related to ambient noise, sensor positioning, process variability, and the lack of standardized measurement and analysis procedures. At the same time, the growing need for intelligent welding systems and solutions within the Industry 4.0 concept has refocused attention on acoustic measurement as a complementary or alternative monitoring method, thanks to its simplicity, non-intrusive nature, and rich informational content (Figure 1). Despite extensive experimental research, a large number of existing studies remain limited to specific applications and do not possess a unique physical framework that would relate acoustic characteristics to basic welding phenomena. In this context, this paper provides a comprehensive overview of acoustic analysis in the GMAW process. The physical sources of welding sound, acoustic measurement approaches, signal processing techniques, and the main areas of application, including process stability monitoring, weld quality assessment, metal transfer mode classification, and defect detection, are presented. Current challenges and future directions of research were also discussed to highlight the potential of acoustic measurement for the development of intelligent and reliable GMAW process monitoring systems. In addition to works focused on specific processes, several review and survey papers have provided a broader methodological and technological context of the application of acoustic and audible sound for real-time monitoring of welding transient phenomena and processes [36-38].

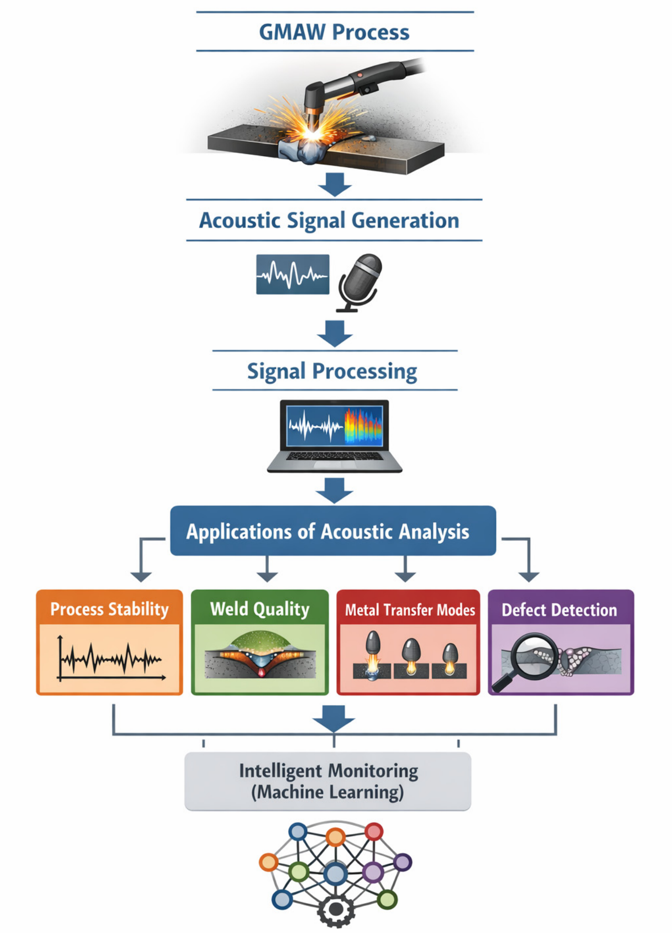

Figure 1: Conceptual workflow of acoustic analysis in GMAW

1.1. Scope and methodology of the review

This review paper focuses on acoustic signal analysis applied exclusively to GMAW. The scope of the paper is deliberately limited to the GMAW process in order to allow a detailed and physically based elaboration of sound generation mechanisms, signal processing approaches, and practical applications relevant to this welding process. The literature reviewed was selected based on its relevance to acoustic measurement, sound emission, or acoustic emission signals techniques in the GMAW process, with particular emphasis on studies dealing with process stability, metal transfer modes, weld quality assessment, and defect detection. Both classic and contemporary works are included in the consideration to cover the historical development of the field, as well as current research trends.

The review gives priority to papers published in peer-reviewed scientific journals and doctoral dissertations, while conference papers are included in cases where they provide a significant methodological or conceptual contribution. Selected studies were analyzed and synthesized in relation to the applied type of sensor, signal features, used models, and processing techniques, as well as basic conclusions and reported results.

1.2. Acoustic sensing modalities in GMAW

Acoustic monitoring of the GMAW process is most commonly performed using microphone-based airborne sound measurements or acoustic emission (AE) sensors that register waves propagating through the material structure. Microphones measure sound pressure fluctuations emitted into the surrounding air and are particularly sensitive to arc plasma dynamics and metal transfer events. Due to their non-contact nature and simple installation, microphone-based systems represent an attractive solution for industrial applications, although they are more susceptible to ambient noise and reflections. In contrast, AE sensors are typically mounted directly on the workpiece and detect elastic waves propagating through the material. Acoustic emission measurements performed using AE sensors are less sensitive to airborne noise and are particularly suitable for the detection of high-frequency transient events, such as crack initiation or burn-through. However, their application requires physical contact and proper mechanical coupling between the sensor and the surface, which may limit their practical applicability in certain industrial environments.

Numerous studies have shown that both approaches provide complementary information about the welding process, and hybrid systems combining microphones and AE sensors have been proposed in order to increase the robustness and reliability of process monitoring. In this review, measurements of airborne sound and measurements of acoustic emission signals through a structure are discussed within the common concept of acoustic sensing, since both types of signals originate from the same basic phenomena in the welding process, but differ in the propagation medium and characteristic frequency range.

1.3. Positioning of acoustic analysis among welding monitoring techniques

Compared to traditional monitoring methods based on electrical and optical measurements, acoustic analysis offers a unique combination of non-intrusiveness, sensitivity to dynamic phenomena, and relatively low implementation costs. Electrical signals, such as welding current and voltage, provide direct information about energy delivery, but are often not sensitive enough to detect subtle disturbances associated with metal transfer or molten pool dynamics. Optical monitoring systems, although extremely informative, as a rule require complex measuring equipment and can be sensitive to harsh conditions in the welding zone, such as intense arc radiation, fume, metal spatter, and lighting changes. Acoustic sensing complements these approaches by providing indirect but physically meaningful information on arc dynamics, metal droplet detachment, and process instabilities. As a result, acoustic analysis is increasingly considered an important component of multi-sensor and intelligent welding process monitoring systems.

2. ACOUSTIC SIGNAL GENERATION IN GMAW

The acoustic signal produced during the GMAW process originates from the interaction of several physical phenomena that take place within the electric arc, the molten metal, and the surrounding shielding gas. Unlike purely electrical or optical signals, welding sound is a macroscopic manifestation of the rapid energy exchanges and dynamic instabilities inherent in the GMAW process. Understanding the origin of acoustic signals is therefore crucial to correctly interpret their relationship to process stability, metal transfer mechanisms, and weld quality.

2.1. Arc plasma dynamics as a sound source

One of the primary sources of acoustic emission in the GMAW process is the electric arc plasma. Temporal fluctuations of current and arc voltage lead to rapid changes in pressure, temperature, and electrical conductivity of the plasma, resulting in periodic expansion and contraction of the plasma column. These pressure oscillations spread into the surrounding environment in the form of acoustic waves and represent a significant part of the measured sound signal [8-10]. In the short-circuit and globular metal transfer modes, abrupt changes in arc length during droplet formation and detachment introduce pronounced transient disturbances in the arc plasma. These events generate pulsed acoustic emissions with broadband frequency content, which are clearly visible in both time domain and spectral representations of the sound signal [22],[23-25]. In contrast, in stable metal spray transfer, the electric arc remains relatively constant, resulting in more continuous acoustic signatures with narrower spectral distributions [26],[39].

2.2. Metal transfer phenomena and droplet dynamics

Metal transfer is widely recognized as one of the dominant sources of acoustic activity in the GMAW process. The formation, growth, detachment, and impact of molten metal droplets are determined by the balance of electromagnetic forces, surface tension, gravity, and drag of the plasma. Each of these mechanisms contributes to the force fluctuations that excite acoustic radiation during the welding process [27,28], [33,34], [40].

The short-circuit transfer mode in particular generates pronounced acoustic pulses associated with repeated arc extinguishing and reignition events. These impulses strongly correlate with the frequency and duration of short circuits, which explains the close connection between statistical acoustic features and process stability, as confirmed in numerous studies [1-5],[29,30]. In contrast, globular and spray modes of metal transfer are characterized by a more uniform behavior during droplet separation, which leads to acoustic emissions dominated by periodic components associated with droplet oscillations and their detachment frequency [28],[33,34].

Newer research has additionally shown that the resonant phenomena of droplets and their oscillatory movement can significantly affect the acoustic spectrum, especially in the pulsed and controlled GMAW process. Changes in droplet size, droplet detachment time, and impact dynamics result in characteristic acoustic patterns that can be used to classify metal transfer modes and monitor the welding process [11,12], [26], [39].

2.3. Gas flow, arc–droplet interaction, and molten pool dynamics

In addition to arc plasma dynamics and metal transfer, shielding gas flow and interaction between the arc and metal droplets contribute significantly to the overall acoustic emission during the GMAW process. Turbulent gas flow in the arc zone generates broadband noise, while interactions between the plasma jet and the molten metal surface cause pressure fluctuations that further modulate the sound signal [9-12].

The dynamics of the molten metal pool also play a secondary but significant role in the generation of acoustic signals.

Oscillations of the pool surface, especially in conditions of thermal or electromagnetic instability, can be coupled with arc pressure variations and droplet impacts, which lead to the amplification of low-frequency acoustic components, as observed in several experimental studies dedicated to penetration instability and burn-through phenomena [1,2]. These effects become more pronounced in cases of burn-through, excessive penetration, or unstable heat input, which explains the high sensitivity of acoustic signals to the occurrence of weld defects and variations in penetration depth, noted in numerous experimental studies [1-4],[31].

2.4. Statistical and physical interpretation of GMAW sound

From the aspect of signal processing, the acoustic emission during the GMAW process exhibits a stochastic and impulsive character, which reflects the inherently unstable and non-linear behavior of the welding process. Statistical analyses have shown that sound pressure distributions often deviate from the Gaussian distribution and are characterized by "heavy tails", especially in unstable welding modes [11,12],[41]. These properties provide the physical basis for the effectiveness of time-domain statistical features, such as root mean square (RMS), kurtosis, and variance, in characterizing process stability and weld defect formation. In addition to empirical observations, newer models seek to explicitly link the physical parameters of the process with the mechanisms of acoustic signal generation. Lumped-parameter and numerical models, including arc dynamics, metal transfer forces, and energy balance, have provided significant insight into the coupling between the physics of the welding process and sound generation [35]. Such models strengthen the theoretical basis of acoustically based monitoring methods and enable the interpretation of measured signals in the context of basic physical phenomena.

From a practical point of view, the acoustic emission during the GMAW process is characterized by relatively high sound pressure levels and a wide frequency range, where both the amplitude and the spectral distribution are strongly dependent on the welding parameters and the metal transfer mode [8],[42]. Short-circuit metal transfer is usually associated with impulsive, broadband acoustic emissions originating from arc extinction and reignition, while globular and spray modes of transfer produce more continuous acoustic signatures with dominant frequency components associated with periodic droplet detachment and arc plasma oscillations [9-12]. In the pulsed GMAW process, additional spectral components synchronized with the pulse frequency additionally shape characteristic time-frequency patterns, which differ from those present in conventional metal transfer modes [26],[39],[43,44]. These systematic differences in sound pressure level and spectral content provide the physical basis for the statistical acoustic features and analysis approaches discussed in the following chapters. The overall connection between physical phenomena in the GMAW process, acoustic signal generation, signal processing, feature extraction, and their application in process monitoring tasks is shown schematically in Figure 2.

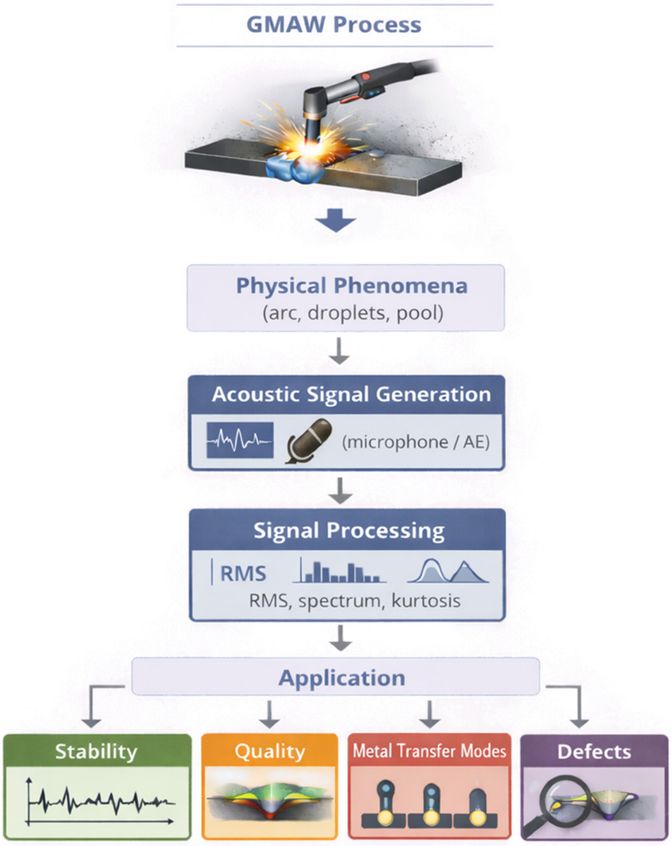

Figure 2: Overview of main application domains of acoustic analysis in GMAW

3. ACOUSTIC MEASUREMENT AND SIGNAL PROCESSING IN GMAW

The effectiveness of the acoustic analysis in the GMAW process is highly dependent on the applied measurement strategy and subsequent signal processing techniques. Given the complex and noisy industrial environment in which GMAW is most often performed, careful selection of acoustic sensors, measurement configurations, and signal processing methods is necessary to ensure reliable extraction of information relevant to the welding process. Over the past decades, various approaches to acoustic monitoring and analysis have been proposed, ranging from simple audible sound measurements to advanced acoustic emission systems combined with machine learning algorithms.

3.1. Acoustic sensing techniques and sensor configurations

Acoustic monitoring of the GMAW process is most often carried out using measurements of airborne sound, based on the use of microphones or using structural AE sensors. Airborne sound measurement relies on microphones placed near the welding arc, which register the audible sound generated during the process. This approach is non-intrusive, simple to implement, and economically viable, which makes it particularly suitable for industrial applications [8],[45,46]. Microphone-based measurements have been successfully applied for online monitoring of welding process stability, metal transfer behavior, and weld quality. Several studies have shown that even a single microphone can provide enough acoustic information for the detection of process instabilities and welding defects, if appropriate signal processing techniques are applied [1,2], [22], [25].

In recent research, systems with microphone arrays have been introduced to improve spatial resolution and resistance to the influence of ambient noise, which enables dynamic localization and monitoring of acoustic sources in the welding zone [47]. Using spatial filtering and beamforming techniques, microphone arrays enable the separation of the sound associated with the welding arc from ambient noise and reflections, which is of particular importance in industrial environments with complex acoustic conditions. Early methodological frameworks for the systematic characterization of the acoustics of the GMAW process, including the selection of sensor positions and frequency ranges, were discussed in [48], which laid the foundation for the later development of spatial and array acoustic monitoring. In addition to process stability monitoring, arc sound measurement has also been applied in spatial process monitoring tasks, such as seam monitoring in GMAW welding in narrow grooves, which further confirms the versatility of microphone-based acoustic measurements [49].

Unlike airborne sound measurement, acoustic emission measurements using AE sensors involve piezoelectric transducers mounted directly on the workpiece or welding fixture to detect high-frequency elastic waves propagating through the material. AE sensors are particularly sensitive to transient microstructural events, such as crack initiation, plastic deformation, and molten metal droplet impact, which is why measurements obtained using AE sensors have been widely applied in welding research and in NDT methods [3],[15],[19]. Compared to microphones, acoustic emission measurements performed using AE sensors are less susceptible to the influence of ambient acoustic noise; however, their practical application requires careful positioning of the sensors and high-quality mechanical coupling with the material. These requirements may limit the applicability of AE sensor-based measurement systems in certain manufacturing environments, despite their high sensitivity to defect-related phenomena.

3.2. Signal acquisition and preprocessing

Acoustic signals collected during the GMAW process are typically characterized by non-stationary behavior, a wide dynamic range, and a pronounced influence of ambient noise. Therefore, signal preprocessing plays a key role in extracting meaningful information from raw measurements. Common preprocessing steps include signal amplification, analog and digital filtering, segmentation, and normalization.

Band-pass filtering is widely used to suppress low-frequency mechanical noise and high-frequency electronic interference, which separates the frequency bands that are most relevant for phenomena in the welding process [9,10],[50]. Signal segmentation, which is usually based on windows of fixed length or synchronized with welding current and voltage signals, allows time-resolved analysis of transient events, such as short circuits and the separation of molten metal droplets [23-25]. In industrial settings, additional noise reduction techniques, including spectral subtraction, adaptive filtering, and robust statistical thresholding, are applied to improve signal-to-noise ratio and increase detection reliability [23],[25]. These procedures are particularly important for microphone-based measurements, which are carried out in acoustically harsh environments typical of welding processes.

3.3. Time-domain and frequency-domain analysis

Time domain analysis is the simplest and historically the earliest approach to the characterization of acoustic signals in the GMAW process. Due to its simplicity and low computational cost, time-domain analysis has been widely applied in both early and modern GMAW process research. The most commonly used statistical acoustic features in the time domain include RMS, peak amplitude, variance, skewness, kurtosis, and zero-crossing rate. These descriptors provide concise statistical representations of the amplitude fluctuations and impulse character of an acoustic signal.

Numerous studies have shown that statistical acoustic features in the time domain are strongly correlated with the stability of the welding process, especially in the short-circuit GMAW mode. Improper metal transfer, arc extinction and enhanced spatter lead to increased signal variability and impulse amplitude distributions, which are effectively detected by means of RMS value, variance, and kurtosis [22], [24,25]. As a result, time domain statistical acoustic features have been successfully used to detect unstable welding conditions and to monitor the regularity of short circuits in real time.

Frequency domain analysis, which is most often based on the fast Fourier transform (FFT), provides complementary information by revealing the dominant frequency components and spectral energy distribution of the welding sound. Spectral analysis enables the identification of periodic phenomena associated with arc dynamics and metal transfer mechanisms, which are not always clearly visible in the time domain. Several studies have shown that different welding regimes and modes of metal transfer have characteristic spectral features, expressed through dominant frequency peaks, changes in spectrum width, and spectral energy concentration [9-12], [51].

Frequency features, such as dominant frequency, spectral centroid, spectral width, and spectral energy ratios, have been effectively applied to classify process stability and metal transfer modes. In stable spray transfer, the acoustic spectrum is typically characterized by more concentrated and narrowband frequency content, while short-circuit transfer produces broadband spectra with pronounced low-frequency components [9,10], [26], [39]. These spectral differences represent the physical basis for the classification of welding modes based on acoustic signals.

Despite their effectiveness, time and frequency domain analyses have inherent limitations when applied to non-stationary welding signals. Conventional FFT methods assume the stationarity of the signal within the analyzed time window, which can lead to the masking of transient events, such as short-circuit transitions and sudden arc disturbances. Therefore, although time and frequency features remain valuable for the global characterization of welding process behavior, they are often supplemented with time-frequency analysis techniques to capture the dynamic evolution of acoustic phenomena during the GMAW process [24].

3.4. Time-frequency analysis and advanced signal processing

Considering the non-stationary character of the acoustic signals generated during the GMAW process, time-frequency analysis methods have attracted considerable attention in modern research. Short-time Fourier transform (STFT) and spectrogram-based analyses allow the simultaneous observation of temporal and spectral signal changes, which makes them particularly suitable for the detection of transient events and the identification of welding process instabilities [24], [25].

More advanced techniques, including wavelet-based methods and other adaptive time-frequency approaches, have been applied to improve time-frequency resolution and increase sensitivity to localized phenomena, such as short-circuit transitions and defect initiation [29,30],[50]. In addition, advanced signal decomposition techniques, such as empirical mode decomposition (EMD), have been used to analyze airborne acoustic signals in welding processes, enabling more accurate characterization of non-stationary acoustic behavior [52].

These approaches enable the adaptive decomposition of acoustic signals into components that can be directly related to the underlying dynamics of the welding process. In this way, time-frequency and adaptive methods significantly contribute to a more precise extraction of statistical acoustic features and a more reliable classification of welding modes and process conditions.

3.5. Statistical acoustic feature extraction and data-driven analysis

The extracted statistical acoustic features represent input quantities for statistical and data-driven models used in monitoring the welding process and evaluating the quality of the welded joint. Classical approaches include correlation analysis, regression modeling, and statistical decision-making methods, where the feasibility of predicting weld quality indicators based on acoustic data has been demonstrated [4,5]. However, most existing data-driven approaches rely on empirical correlations between features and process states, while physically based sound source models are still rarely integrated into such analyses.

In addition to conventional physical and statistical acoustic features, psycho-acoustic descriptors were investigated in a limited number of studies in order to characterize subjectively perceived sound quality during the GMAW process. These works indicate a potential connection between human auditory perception and the stability of the welding process, further confirming the informational value of the acoustic signal [13].

In recent years, ML techniques, such as support vector machines (SVM), artificial neural networks (ANN), and convolutional neural networks (CNN), have been increasingly applied in the analysis of acoustic signals in GMAW. These approaches enable automated classification of metal transfer modes, detection of process anomalies, and prediction of weld quality with increased model robustness and adaptability [29-32], [53]. Despite the encouraging results, the success of such models still largely depends on the quality of signal acquisition, preprocessing procedures, and the selection of relevant features.

It should be emphasized that the goal of this review paper is not an exhaustive consideration of the theory of signal processing and ML, but to highlight representative approaches that have shown practical relevance for the acoustic analysis of the GMAW process.

4. APPLICATIONS OF ACOUSTIC ANALYSIS IN GMAW

Acoustic analysis has been intensively researched over the past decades as a non-intrusive and information-rich method for monitoring and diagnostics of the GMAW process. Due to its sensitivity to arc behavior, metal transfer dynamics, and molten pool instability, acoustic measurement has found application in several key areas of GMAW process analysis, including process stability monitoring, weld quality assessment, metal transfer mode classification, and weld defect detection (Figure 2). This chapter provides a structured overview of the main application areas of acoustic analysis identified in the relevant literature.

4.1. Process monitoring and stability assessment

One of the earliest and most frequently researched applications of acoustic analysis in the GMAW process is process stability monitoring. Welding stability is closely related to metal transfer regularity, arc length consistency, and controlled heat input, all of which directly affect the acoustic emission generated during welding. Numerous studies have shown that stable and unstable welding modes exhibit clearly different acoustic characteristics in the time and frequency domains, thus confirming the sensitivity of sound signals to changes in process stability [22-25].

In the short-circuit GMAW process, instability is most often associated with irregular short circuit durations, increased metal spatter, and arc extinction. These phenomena lead to the appearance of impulsive acoustic emissions characterized by increased amplitude variability and broadband spectral content. It has been shown that temporal acoustic parameters, such as RMS, variance, and kurtosis, strongly correlate with the regularity of short circuits and the overall stability of the welding process [1-5], [25].

Analyzes in the frequency and time-frequency domains further increase the sensitivity to transient disturbances, enabling the early detection of unstable operating conditions that may not be clearly observed solely based on electrical current and voltage signals [23,24]. Several authors pointed out that acoustic monitoring of process stability can complement, and in certain cases replace, conventional analysis of electrical signals, especially when current and voltage measurements are not sensitive enough to subtle disturbances in arc behavior.

An additional advantage of acoustic process monitoring is reflected in the non-contact character of microphone-based measurements, which makes this method particularly suitable for industrially oriented research and experimental applications where sensor integration and maintenance requirements are of key importance [45,46]. In addition to single-sensor approaches, spatially distributed measurements using microphone arrays have been proposed to increase robustness and spatial resolution in dynamic monitoring of welding processes, especially in industrial environments with complex acoustic conditions [47]. In addition to stability assessment, arc sound analysis has also been successfully applied in spatial process monitoring tasks, such as seam monitoring in GMAW procedures with a narrow gap, which further confirmed the versatility of acoustic signals in monitoring welding processes [49].

4.2. Weld quality evaluation and penetration assessment

In addition to process stability monitoring, acoustic analysis has been intensively researched in the context of weld quality assessment, including penetration depth, weld geometry, and overall weld integrity. Changes in heat input, arc behavior, and weld pool dynamics directly affect the acoustic emission generated during the GMAW process, making sound signals sensitive indicators of weld formation and weld quality. In this way, acoustic measurement enables a non-contact and indirect approach to the assessment of weld quality in real time during the welding process itself.

Numerous studies have indicated a strong correlation between statistical acoustic parameters and penetration conditions during GMAW. Temporal and spectral descriptors of arc sound have been shown to reflect changes in weld pool behavior associated with insufficient or excessive penetration [14], [31], [50],[54]. Unstable penetration conditions often lead to increased variability of the acoustic signal and the appearance of characteristic spectral patterns, which makes it possible to separate acceptable welds from those with defects.

Regression and statistical models are widely applied to quantify the relationship between statistical acoustic parameters and weld quality indicators. Shahabi and Kolahan [5] showed that acoustic signals contain complementary information compared to conventional electrical parameters, whereby combining these two types of signals leads to an increase in the accuracy of quality prediction. These results confirm the potential of acoustic measurement as a soft-sensor approach for online assessment of weld quality parameters.

More recent research is focused on the application of ML methods to improve the assessment of weld quality based on acoustic data. ANN, SVM, and deep learning models have been successfully used to classify penetration states and predict quality metrics under controlled experimental conditions [5], [31,32]. These approaches enable the automated interpretation of complex acoustic patterns that are often difficult to capture with classical methods based solely on manually defined features.

Given that welding technique and process stability directly affect local stresses, deformations, and microstructural evolution in welded joints, acoustic signals that reflect these dynamic phenomena can also be seen as indirect indicators of the structural integrity of the weld [55]. Nevertheless, despite the encouraging results, the robustness and general applicability of acoustic models for quality assessment are still limited by process variability, the influence of ambient noise, and differences in experimental and industrial settings. These limitations point to the need for further validation and integration of acoustic measurement with complementary sensing approaches in industrial applications.

4.3. Acoustic-based classification of metal transfer modes

The classification of metal transfer modes represents one of the most important areas of application of acoustic analysis in GMAW. Different transfer modes - short-circuit, globular, spray, and pulse are based on different droplet formation and separation mechanisms, which largely determine arc stability, heat input, spatter occurrence, and weld quality. As these physical processes directly affect pressure fluctuations in the arc and molten metal, they are naturally reflected in the emitted acoustic signal. Figure 3 shows schematically the characteristic physical behavior and corresponding acoustic signatures associated with different modes of metal transfer in the GMAW process.

Experimental research has consistently shown that each metal transfer mode possesses characteristic acoustic signatures. Short-circuit metal transmission is associated with pulsed acoustic patterns synchronized with arc extinguishing and reignition events, resulting in broadband spectral content and high temporal variability of the signal. In contrast, spray metal transfer generates more continuous and stable acoustic emissions, dominated by periodic components associated with droplet separation frequency [9,10],[27,28]. In the pulse GMAW procedure, additional modulation effects appear, which lead to the appearance of characteristic time-frequency structures in the acoustic signal [33], [34].

Time-frequency representations, such as spectrograms and STFTs, have proven particularly effective for analyzing transitions between different metal transfer modes and identifying unstable operating regions. These methods enable the visualization of transient events and periodic structures that are difficult to observe using only temporal or frequency analysis [24],[29,30]. Therefore, time-frequency features are widely used as discriminative descriptors in the classification of metal transfer modes.

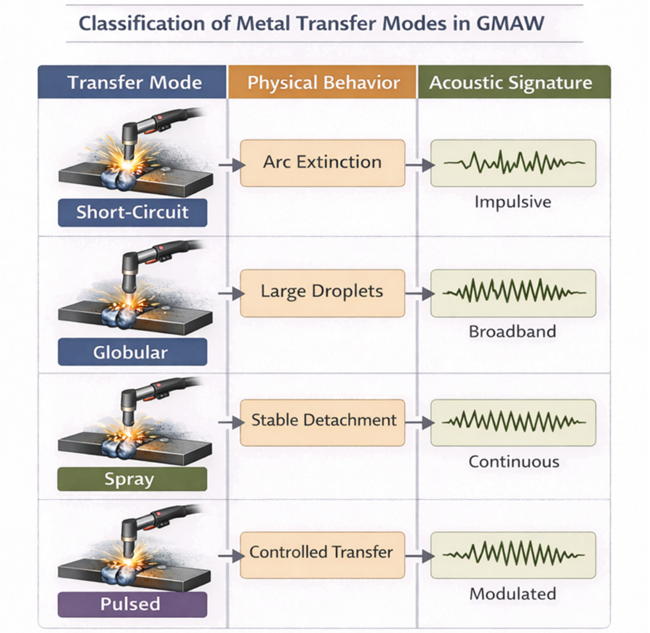

Figure 3: Classification of metal transfer modes in GMAW and their corresponding physical behavior and acoustic signatures

In recent research, increasing attention has been paid to the automated classification of metal transfer modes using acoustic features in combination with ML methods. Supervised approaches, including ANNs and other classifiers, have demonstrated reliable transmission mode discrimination based solely on sound measurements [11,12], [26], [39], [56]. These results indicate the feasibility of identifying metal transfer modes without direct access to electrical signals, which is particularly relevant for non-contact process monitoring and adaptive control applications.

Despite the encouraging results, the robustness of the acoustic classification of the metal transfer mode is still affected by process variability, sensor position, and ambient noise. In transient or unstable welding modes, overlapping acoustic characteristics may occur, making it difficult to clearly separate the modes. Therefore, acoustic classification is often most effective when combined with complementary sensory approaches or physically based constraints. Nevertheless, the strong connection between metal transfer physics and acoustic emission validates sound analysis as a powerful tool for identifying metal transfer modes and represents a natural link between process stability assessment and weld quality evaluation.

4.4. Detection and identification of welding defects

The detection and identification of welding defects is one of the earliest and most established areas of application of acoustic measurement in welding processes. Acoustic emission techniques have a long tradition in the field of NDT and are among the first methods to demonstrate the possibility of detecting phenomena associated with errors in real time, during the welding process itself. Pioneering research by Jolly [15,16] showed that acoustic emission signals can detect crack initiation, porosity occurrence, and the presence of inclusions during welding and subsequent cooling of the weld metal, thus highlighting the potential of acoustic monitoring for in-process defect detection.

In the GMAW process, various types of defects, including burn-through, lack of fusion, porosity, and crack formation, are associated with characteristic disturbances in arc behavior and molten pool dynamics, which are reflected in the acoustic signal. Experimental research has shown that sudden changes in acoustic emission energy, impulse activity, and frequency content of the signal are closely related to mechanisms of error initiation and growth [3], [18,19], [57,58]. These results established a direct link between physical events associated with defects and measurable statistical acoustic features.

Burn-through detection represents one of the most successful and extensively researched applications of acoustic monitoring in the field of defect identification. Rapid changes in molten pool stability and excessive heat input generate characteristic acoustic signatures that can be detected earlier than by visual inspection or post-process NDT methods [1-3], [19]. The sensitivity of acoustic signals to these transient events enables the timely identification of critical defects and supports the implementation of corrective interventions during the process.

In addition to the detection itself, several studies investigated the possibility of classifying the types of defects based on the characteristics of the acoustic emission. Parameters such as signal energy, amplitude distribution, and frequency content have been linked to specific defect mechanisms, allowing the distinction of lack of fusion, porosity-related phenomena, and other imperfections [3,4],[59]. These approaches confirm that acoustic features contain defect type-specific information, although reliable classification often requires careful feature selection and appropriate calibration.

In recent research, increasing attention has been paid to the application of data-based methods to improve the detection and identification of defects using acoustic signals. ML techniques have been applied to acoustic data to automatically recognize defect-related patterns and process anomalies with greater robustness compared to rule-based methods [4], [29,30], [32]. These approaches are particularly promising for complex industrial environments, but their success still depends on data quality, labeling accuracy, and process variability.

Despite its proven effectiveness, acoustic defect detection in the GMAW process faces limitations related to ambient noise, overlapping acoustic signatures, and sensitivity to sensor position. Statistical acoustic features associated with defects can overlap with signals generated by transient but non-destructive process instabilities, making reliable identification difficult under certain conditions. Therefore, defect detection is most effective when acoustic measurement is combined with complementary monitoring methods or integrated into multi-sensor systems. Nevertheless, the proven ability of acoustic analysis to detect and characterize welding defects in real time highlights its importance as a non-contact diagnostic method within intelligent GMAW process monitoring systems.

5. CHALLENGES AND FUTURE RESEARCH DIRECTIONS

Despite the significant progress achieved in the application of acoustic analysis in the GMAW process, numerous technical and methodological challenges still limit its wider industrial application. At the same time, the development of new technologies and modern research directions opens up new opportunities for the improvement of acoustically based monitoring and management of GMAW processes.

5.1. Challenges in acoustic-based monitoring of GMAW

One of the main challenges associated with the application of acoustic measurement in the GMAW process is the pronounced sensitivity to ambient noise. Industrial environments where welding is most commonly performed are characterized by high levels of ambient noise, originating from auxiliary equipment, ventilation systems, and adjacent manufacturing operations. This problem is particularly pronounced when measuring sound in the air using a microphone, where reflections and ambient disturbances can significantly degrade the quality of the signal [25], [45].

Although some noise effects can be mitigated by applying appropriate signal preprocessing and filtering techniques, reliable noise suppression still represents one of the key challenges.

Sensor position and measurement configuration represent additional sources of acoustic signal variability. The measured acoustic signal strongly depends on the relative position of the microphone or AE sensor in relation to the arc, the geometry of the workpiece, and the fixture conditions. As a result, repeatability and comparability of acoustic measurements between different experimental and industrial settings are difficult to achieve without clearly defined and standardized guidelines [9,10],[46]. The absence of standardization further limits the transferability of acoustically based models between laboratory research and real industrial applications.

An additional challenge is the complex and non-linear relationship between statistical acoustic features and physical phenomena in the welding process. The acoustic signal is simultaneously influenced by arc dynamics, metal transfer behavior, shielding gas flow, and molten metal pool oscillations, which significantly complicates the physical interpretation of isolated features [11,12],[35]. Although data-driven models have shown encouraging performance, their dependence on large and reliably annotated data sets raises issues of overlearning and generalization, especially when changing welding parameters, material type, or joint configuration [29,30],[32].

5.2. Integration with multi-sensor and intelligent welding systems

Future research in the field of acoustically based monitoring of GMAW processes is expected to increasingly focus on the integration of acoustic measurement with other monitoring modalities, such as electrical signals, optical sensors, and thermal measurements. Each of these measurement techniques covers different aspects of the welding process, while their combination allows a more complete and robust representation of the process behavior. In this context, acoustic signals represent a valuable complementary source of information, thanks to their sensitivity to dynamic phenomena and their non-intrusive nature.

It has been shown that data fusion from multiple sensors significantly improves the reliability and robustness of welding process monitoring, compensating for the limitations of individual measurement methods. Electrical signals provide direct information on energy delivery, while optical and thermal measurements provide spatially resolved insight into the behavior of the arc and molten metal pool. Acoustic measurement complements these techniques by recording indirect but physically meaningful manifestations of arc dynamics, metal transfer, and process instabilities [6,7]. As a result, hybrid monitoring systems can realize increased sensitivity to subtle process disturbances and early stages of defect formation.

Growing interest in intelligent welding systems and Industry 4.0 concepts has further stimulated research aimed at integrating acoustic measurement into data-driven frameworks for process monitoring and control. ML methods enable automatic feature extraction, anomaly detection, and classification based on heterogeneous sensor data sets, including acoustic signals. Recent research has shown that acoustic information can significantly improve the performance of intelligent monitoring systems when combined with other sensory inputs, especially in quality prediction and anomaly detection tasks [31,32], [38].

In addition to monitoring, acoustic measurement has also been investigated as an input for adaptive control and robotic welding systems. Early cognitive and learning welding concepts demonstrated the feasibility of using acoustic data to guide process corrections and support automated decision-making in robotic environments. These early approaches represent important precursors to modern intelligent welding systems, in which real-time feedback is used to optimize process parameters and ensure consistent weld quality.

Despite the encouraging results, the integration of acoustic measurement into multi-sensor and intelligent welding systems still faces significant challenges. Differences in sampling rates, data synchronization, sensor placement, and signal interpretation make efficient data fusion difficult. In addition, many data-driven models still suffer from a lack of physical interpretability, which may limit their acceptance and confidence in industrial applications. Therefore, future research should be directed towards the development of physically informed and explainable models, standardized data fusion strategies and robust validation under different welding conditions and for different materials, to fully exploit the potential of acoustic measurement within intelligent GMAW process monitoring systems.

5.3. Toward physically grounded modeling and standardization

One of the key directions of future research in the field of acoustic analysis of the GMAW process is the development of physically based models capable of explaining and predicting the mechanisms of sound generation during welding. Although numerous experimental studies have shown strong correlations between statistical acoustic features and welding process behavior, most existing approaches rely on empirical relationships. Such an approach limits their general applicability and predictive power, especially when changing process parameters, materials or geometry of the welded joint.

Recent research efforts have begun to overcome this gap by developing analytical and numerical models that explicitly link arc plasma dynamics, metal transfer behavior, and energy release mechanisms to acoustic emission. Lumped-parameter models and simplified physical representations provided valuable insight into the coupling between welding physics and sound generation, further strengthening the theoretical basis of acoustically based process monitoring [35]. However, these models often include simplifying assumptions and remain limited in their ability to fully capture the complex, nonlinear, and multi-physics nature of the GMAW process.

Further progress in this area is expected to benefit significantly from a closer integration of physical modeling and data-driven approaches. Physically informed ML models represent a promising direction towards improved interpretability and robustness, as they enable the incorporation of domain knowledge into data-driven frameworks. Such hybrid approaches could reduce the dependence on large, precisely labeled data sets, while improving the ability to extrapolate to previously unexplored welding conditions, thereby addressing one of the key limitations of purely empirical acoustic analysis.

In parallel with the improvement of physical modeling, the establishment of standardized measurement procedures and analysis methodologies is a necessary step towards the maturation of acoustically based welding monitoring. Currently, there is considerable variability in the literature regarding sensor types, their positioning strategies, analyzed frequency ranges, feature definitions, and evaluation criteria. The absence of standardization makes it difficult to compare results and slows down the transfer of research achievements to industrial practice. The development of consensus guidelines for acoustic measurements in the GMAW process would contribute to greater reproducibility, comparability and wider acceptance of this technology.

Efforts toward standardization, combined with improved physical modeling, would significantly increase the credibility and industrial relevance of acoustic measurement. Clearly defined measurement protocols and physically interpretable models would enable reliable verification, validation, and integration of acoustic monitoring systems into production environments. Ultimately, the convergence of physically based understanding, data-driven intelligence, and standardized practices is expected to play a key role in transitioning acoustic analysis from a promising research tool to a reliable component of intelligent systems for monitoring and managing GMAW processes.

6. CONCLUSIONS

This paper provides a comprehensive overview of the application of acoustic analysis in GMAW, with special emphasis on its role as a valuable supplementary method for monitoring the welding process, especially in applications that require real-time insight into dynamic phenomena during welding. The reviewed literature shows that the acoustic signals generated during the GMAW process originate from fundamental physical phenomena, including arc plasma dynamics, metal transfer behavior, shielding gas flow, and molten pool oscillations. As a consequence, welding sound inherently reflects key aspects of process stability and weld formation.

During decades of research, acoustic measurement has been successfully applied to a wide range of tasks associated with the GMAW process. These applications include real-time process stability monitoring, metal transfer mode classification, weld quality and penetration depth assessment, as well as welding defect detection, such as penetration, lack of fusion, and porosity. Techniques based on audible sound and acoustic emission have been shown to provide valuable and complementary information compared to conventional electrical and optical measurement methods, especially in applications requiring non-contact monitoring and real-time process monitoring.

6.1. Scope and contribution of the review

Unlike earlier review papers that consider acoustic measurement in welding at a broader or predominantly technological level, this review paper provides a focused and physically grounded synthesis of acoustic analysis, specifically applied to the GMAW process. By explicitly relating sound generation mechanisms to arc plasma dynamics, metal transfer behavior, and molten pool phenomena, the work contributes to bridging the gap between welding physics and signal analysis-based approaches for process monitoring. Compared to previous reviews, this paper uniquely emphasizes the physical interpretation of acoustic signals in the context of arc dynamics and metal transfer mechanisms in the GMAW process. Additionally, the paper systematically categorizes the primary application areas of acoustic analysis in the GMAW process, including process stability assessment, weld quality evaluation, metal transfer mode classification, and welding defect detection. Contemporary trends towards intelligent, data-driven, and multi-sensor welding systems are also highlighted, providing a coherent frame of reference for both researchers and practicing engineers. The analyzed literature as a whole shows the diversity of sensor approaches, analysis methods, and application areas of acoustic analysis in the GMAW process, ranging from early rule-based systems to modern systems based on ML and data analysis.

6.2. Current limitations and future perspectives

Advances in the field of signal processing and data-driven analysis have significantly expanded the possibilities of acoustic monitoring of the welding process. The characteristics in the time, frequency, and time-frequency domains, in combination with statistical methods and ML algorithms, enabled an increasingly precise classification and prediction of the state of the welding process. The latest developments in the field of artificial intelligence and intelligent welding systems, conceptually illustrated in Figure 4, indicate the growing potential of integrating acoustic measurement into adaptive control frameworks and production environments based on Industry 4.0 concepts.

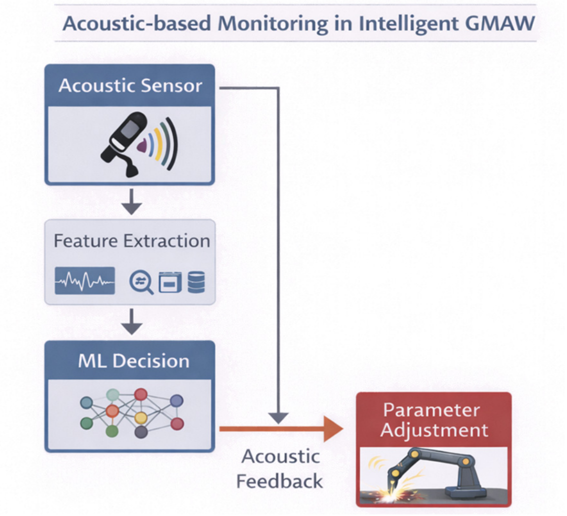

Figure 4: Conceptual framework of acoustic-based monitoring and intelligent control in GMAW

Despite these achievements, significant challenges remain, including sensitivity to ambient noise, dependence on sensor position, limited standardization, and the complexity of interpreting statistical acoustic features in highly dynamic welding conditions. Overcoming these limitations will require continuous development of robust signal processing methods, efficient data fusion from multiple sensors, physically based modeling of sound generation mechanisms, as well as establishment of standardized measurement and evaluation procedures.

Taken as a whole, acoustic analysis represents a mature but still evolving research area with significant potential for improving the monitoring and management of GMAW processes. Further integration of physical process understanding, advanced signal processing methods, and intelligent data-driven approaches is expected to further strengthen the role of acoustic measurement as a practical and reliable tool for ensuring weld quality and process stability in modern welding applications.

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