

Techniques for Monitoring and Fault Diagnostics of Industrial Plasma Processes and Applications

Shakti Prasad Sethi, Mohit Kumar Joshi

Abstract—Plasma science and technology are considered an important source of applications for various industrial processes and scientific research. The scope of plasma sources is applied in various areas of science and engineering disciplines to leverage new applications with better efficiency and productivity. This article presents various techniques developed for monitoring plasma processes and discusses methods applied to diagnosing fault events during operation. It reviews the application of sensors, probes, and invasive as well as non-invasive diagnostic techniques for fault detection and mitigation of challenges in plasma systems. In this article, the role of signal and image processing techniques in fault event diagnosis is highlighted. The study also highlights the application of machine learning and optimization methods for fault classification and the optimization of plasma processes. Schematic representations of key experimental setups incorporating various sensing techniques are presented to facilitate better understanding, and the associated application-specific techniques are also explained. This article presents a comprehensive review of implemented techniques for identifying fault events in plasma processes, optimizing overall process efficiency, and enhancing system performance.

Index Terms—Fault monitoring, plasma diagnostics, process optimization, signal processing, image processing.

I. INTRODUCTION

Plasma is commonly regarded as the fourth state of matter, following the solid, liquid, and gaseous states. It is formed when sufficient energy is supplied to a gas, causing the atoms or molecules to ionize into a mixture of ions, electrons, and neutral species [1]. Based on the physicochemical properties of the dissociated species, plasma processes are broadly classified into two categories: thermal and non-thermal plasmas, also referred to as equilibrium and non-equilibrium plasmas, respectively. Plasma science and technologies are widely employed across various industrial sectors and scientific research domains. Plasma-based processes are applied in areas such as waste treatment [2], mineral processing [3], pyrolysis [4], thermal barrier coating [5], biomedical treatment [6], *etc.* Plasma-treated processes are applied in materials science, agriculture, and water treatment to improve the quality, efficiency, and durability of the process and applications.

Plasma processes extend beyond laboratory research and microscopic analysis and are widely adopted in industrial sectors to meet societal demands and promote economic sustainability. Frequently reported events in industrial plasma processes reduce the attractiveness and user-friendliness of plasma-based systems. Several commonly reported fault events in industrial plasma processes, such as arc extinction [7] and

thermal plasma instabilities, result in electrical energy losses and inefficient material processing [8]. Additionally, events such as improper plasma jet length [9], arcing in dielectric barrier discharge systems [10], and other critical phenomena observed in non-thermal plasma processes contribute to operational inefficiencies and energy losses. Therefore, real-time monitoring and fault detection of plasma processes are essential to ensure uninterrupted operation.

This article presents essential monitoring and fault diagnosis techniques applied to identify fault events in industrial plasma processes, as depicted in Fig. 1. It also reports the methods to reduce the occurrence of uncertain events while improving the efficiency of plasma-assisted technologies. The article begins by discussing the role of sensors, probes, and invasive and non-invasive diagnostic methods in detecting fault events, whose occurrences are subsequently inferred through signal and image processing techniques. Additionally, the article explores advanced algorithms and artificial intelligence-based machine learning techniques for optimizing plasma processes.

The paper is structured in seven sections. Section II provides an overview of the types of industrial plasma processes. Section III presents the sensor techniques used for the fault event detection in plasma processes. Sections IV and V discuss the signal and image processing methods applied to diagnose fault events of industrial plasma processes, respectively. Perspectives and future directions are discussed in section VI. Section VII concludes the paper.

II. TYPES OF INDUSTRIAL PLASMA PROCESSES

The following section provides a brief overview of various industrial plasma processes. These processes are employed in a wide range of applications under both thermal and non-thermal operating conditions.

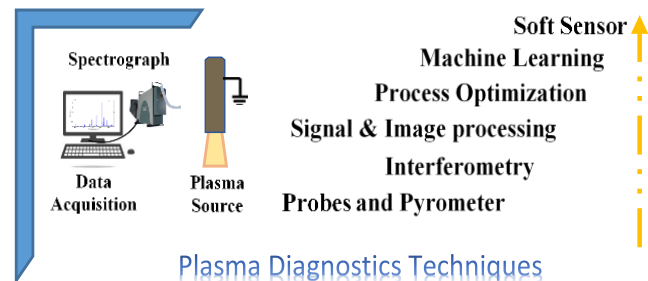


Fig. 1. Schematic representation of monitoring and fault diagnosis techniques for industrial plasma processes discussed in this study.

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A. Electric Arc Plasma

Arc plasma technology was the earliest plasma-based technique developed in the early nineteenth century [11], [12], [13]. Arc plasma systems are capable of generating high-temperature, high-energy-density plasmas through an electric arc established between electrodes. Owing to this capability, they are preferred over conventional methods for applications such as mineral ore smelting, industrial scrap melting, slag processing, fertilizer and biochar production, and nanoparticle synthesis. These systems typically operate using either an alternating current (AC) or a direct current (DC) under atmospheric conditions and commonly employ graphite or tungsten electrodes for smelting operations.

B. Arc Plasma Welding

Arc plasma welding is one of the sophisticated welding techniques currently preferred over other conventional welding techniques [14]. Plasma arc welding utilizes optimal electrical energy and features sophisticated control measures for welding metals without introducing impurities on the surface. Plasma arc welding utilizes different atmospheric gases to clear impurities and prevent the creation of porosity during welding. It is widely used in aircraft manufacturing, avionics, high-speed vehicles, *etc.*

C. Arc Plasma Cutting

Arc plasma cutting technology is widely employed in industrial applications such as cutting metal sheets and drilling metal surfaces. Recognized as a highly precise machining tool [15], it enables accurate machining of metals, steels, and alloy components. The arc plasma cutter provides excellent control over arc length and injection, in addition to being user-friendly and easy to handle.

D. Thermal Plasma Torch

A thermal plasma torch generates a high-temperature, elongated arc using fixed electrodes and typically operates with AC. This configuration, also known as a non-transferred thermal arc plasma, has fixed electrodes from where the arc is generated. It employs tungsten electrodes to withstand extreme temperatures. Characterized by its elongated arc, the high-temperature plasma torch is an advanced industrial plasma technology used in pyrolysis processes [16], nuclear waste treatment, and the decomposition of highly hazardous industrial wastes.

E. Plasma Spray Coating

Plasma spray coating is a high-temperature coating technology [17] that uses powder material (metal powder or alloy powder) to coat metal or ceramic surfaces. The metal powder is fed at the top of the nozzle flame in the plasma setup, and the molten powder particles (splats) strike the target to coat its surface. It is highly recommended for thermal barrier coating, high-temperature coating, heat-resistant coating, and corrosion-free coating. Thermal plasma spray technologies are widely used in nuclear power plants, the aerospace industry, and other sectors for coating components and spare parts.

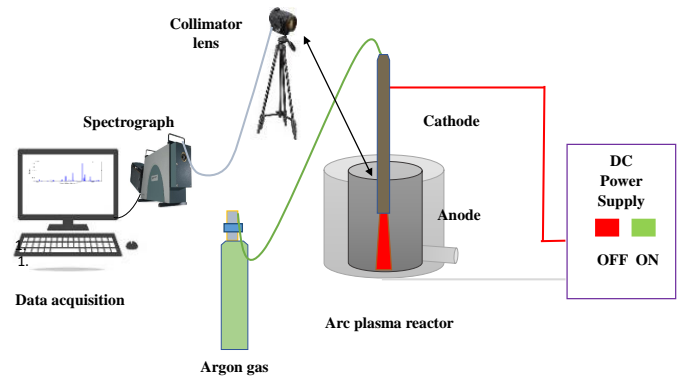


Fig. 2. Optical emission spectroscopy (OES) was used for in-situ monitoring of reactive species during smelting operations in a transferred arc plasma (TAP) setup, while current and voltage measurements were obtained to track arc fluctuations [19].

F. PECVD

Plasma-enhanced chemical vapor deposition (PECVD) is a material fabrication technique employed for surface coating [18]. It utilizes various precursor gases to deposit a thin coating layer on the substrate surface. PECVD is particularly valuable for the fabrication of thin films, substrate wafers, and other materials, and finds extensive applications in the glass, optical, and ceramic industries.

G. Microwave Sputtering

The microwave sputtering technique is employed for material deposition on substrates [21]. In this process, sputtering occurs under the excitation of a microwave source, causing metal vapor to deposit on the substrate and form a thin coating layer. This technique is widely used for fabricating advanced materials, producing insulating glass and fiber components, and supporting material fabrication applications.

H. Dielectric barrier discharge

Dielectric barrier discharge (DBD) plasma [22] is a non-thermal plasma generated by an electrical discharge be-

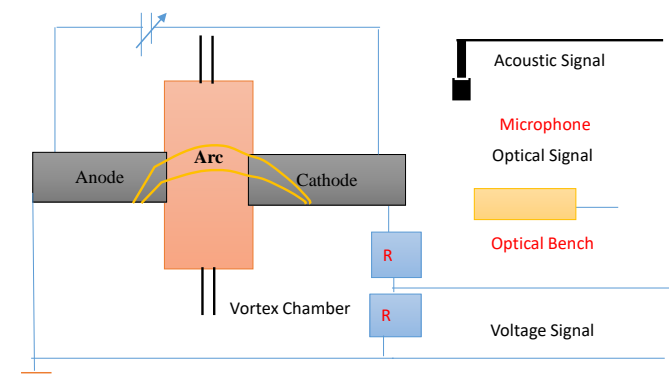


Fig. 3. The plasma torch is equipped with multiple sensing techniques to monitor arc fluctuations resulting from variations in operating parameters. A microphone is used to capture acoustic signals associated with arc fluctuations, an optical sensor records variations in plasma glow intensity, and a voltage sensor is installed around the high-temperature plasma torch [20].

tween two insulated electrodes. The discharge dissociates air molecules into ions, neutrals, radicals, and ozone, which can further react with substances placed between the electrodes to induce ionization. DBD plasma technology is widely applied in crop bacterial treatment, material characterization, water purification, and various biomedical applications.

I. Atmospheric Plasma Jet

This technology is also referred to as cold plasma, as the temperatures of the dissociated ions and electrons differ, producing an optimum-temperature plasma jet suitable for sensitive applications. Unlike thermal plasma, the plasma jet does not exert a significant thermal impingement effect upon contact [23], making it safe for direct interaction with biological tissues and delicate materials. Cold plasma has found extensive applications in wound healing, bacterial disinfection, water purification, and other biomedical treatments.

J. Non-thermal Plasma Etching

Plasma etching can be broadly classified into thermal and non-thermal plasma etching techniques. Non-thermal plasma etching is primarily used to clean the substrate surface prior to material deposition [24], ensuring improved adhesion and surface uniformity. This technique plays a crucial role in defining the morphology and structure of materials during fabrication. In addition to substrate preparation, plasma etching is extensively employed in the glass coating industry to produce impurity-free and smooth surfaces. Beyond glass processing, non-thermal plasma etching is also applied in semiconductor manufacturing, thin film fabrication, and the production of advanced electronic devices due to its precision and ability to selectively remove surface contaminants without damaging the underlying substrate.

K. Atmospheric Plasma Corona Discharge

Corona discharge occurs when atmospheric gas undergoes electrical breakdown at room temperature under ambient conditions [25]. This phenomenon generates a non-thermal plasma rich in ions, electrons, and reactive species, which interact with surface materials to modify their chemical and physical properties. Corona discharge is widely applied in the treatment of paperboard, metalized surfaces, and polymer films to enhance surface wettability, adhesion, and printability.

L. Dielectric Barrier Discharge Micro-plasma

Micro-plasma is a form of dielectric barrier discharge (DBD) [26]. It is generated when two thin films are placed in close proximity, separated by a gap of a few millimeters, and plasma-forming gas is introduced between them. The resulting micro-plasma produces highly reactive species in a confined region, enabling precise surface modification. Its applications are widespread in device fabrication, plasma displays, particle removal, and surface cleaning.

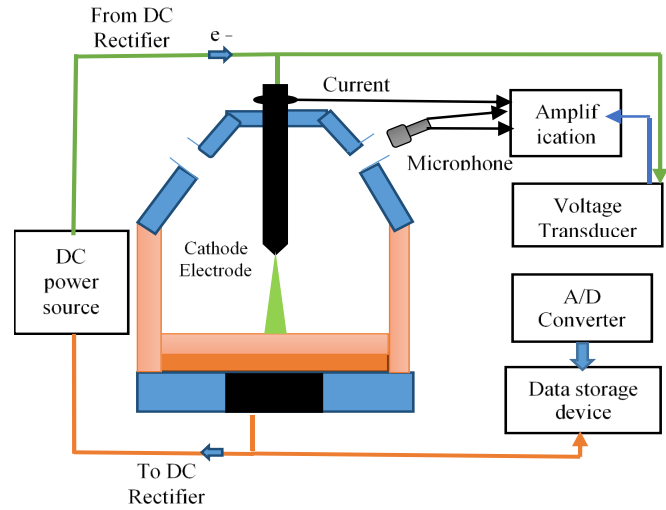


Fig. 4. A multi-sensor arrangement comprising acoustic, current, and voltage sensors is around a transferred arc plasma reactor to monitor arc fluctuations during mineral ore smelting [7], [3].

M. Plasma-activated Water

When a non-thermal atmospheric plasma is applied just above a water surface, the plasma generates reactive ions by dissociating gas molecules in the surrounding air and producing ozone. These ions interact with the water molecules to produce plasma-activated water (PAW) [27]. PAW contains reactive oxygen and nitrogen species that confer antimicrobial properties and stimulate biochemical activity. This technology is increasingly utilized in seed germination, agricultural applications, and antibacterial treatments in the food processing industries.

N. Plasma Deodorization System

Another emerging non-thermal plasma process is employed to trap moisture particles from the air, called plasma deodorization. This technique is widely used for air purification, odor removal, and contaminant mitigation [28]. A summary of industrial plasma processes, categorized based on thermal and non-thermal types, is presented in Table I, highlighting their operating principles, typical applications, and advantages in various industrial sectors.

III. EVENT DETECTION THROUGH SENSORS

Fault monitoring and detection in plasma processes are performed using various sensors and non-invasive diagnostic techniques. The responses obtained from these embedded methods provide critical information on plasma process operation and enable accurate interpretation of event characteristics. For instance, real-time events such as arc fluctuations, arc instability, and electrode erosion are commonly reported faults in arc plasma systems, and these events are identified through analysis of current and voltage signals [43].

In thermal plasma processing, the transferred arc plasma (TAP) setup has been widely employed for the extraction or reduction of minerals from ores, including low-grade ores [19]. To assess the degree of reduction during the smelting

TABLE I
INDUSTRIAL PLASMA PROCESSES

Plasma processes	Types of plasma	Power source	Application
Electric Arc plasma	T	AC/DC	Melting/Smelting of mineral ores, scrap, and slag
Arc plasma welding	T	AC/DC	Efficient welding technique to achieve minimum porosity in welding and reduce impurities in the surface
Arc cutting	T	AC/DC	High-temperature machining, metal sheet cutting
Thermal Plasma torch	T	AC/DC/RF/Microwave	Pyrolysis and extractive metallurgy
Plasma spray coating	T	AC/DC	Thermal barrier coating
PECVD	NT	AC/DC/Microwave	Material fabrication and coating surface
Microwave sputtering	NT	AC/DC/Microwave	Material fabrication and coating surface
Dielectric barrier discharge	NT	AC/DC/Microwave	Bacterial disinfection, biomedical treatment, and Material characterization
Cold atmospheric plasma jet	NT	AC/DC/Microwave	Biomedical application, wound healing
Non-thermal plasma etching	NT	AC/DC/Microwave	IC fabrication, Semiconductor device fabrication
Atmospheric plasma Corona discharge	NT	AC/DC/Microwave	Electrostatic Precipitators (ESPs) for removing dust in the flue gas
Dielectric Barrier Discharge Micro-plasma	NT	AC/DC/Microwave	Photo-catalysis applications and material fabrication
Plasma-activated water	NT	AC/DC/Microwave	Antimicrobial effectiveness and applications in the food industry
Plasma deodorization system	NT	AC/DC/Microwave	Odor removal, air purifier

* T: Thermal plasma, NT: Non-thermal plasma

process under TAP conditions, it is essential to estimate key plasma parameters such as plasma temperature and species density in order to effectively monitor process progression. To effectively monitor the reduction process, optical emission spectroscopy (OES) serves as a non-invasive sensing technique for tracking the reduction process through variations in the emission intensity of excited species. OES is a useful method for monitoring the reduction progress of ores, as illustrated in Fig. 2. In Fig. 2, a collimator lens is employed to focus on the arc plasma generated inside the furnace, while the OES system and a personal computer are positioned at a suitable distance from the reactor to record and analyze the emission spectra of reactive species. Similarly, a pyrometer is also used to measure the temperature of the furnace and the molten bath in electric arc plasma systems. These devices are capable of measuring plasma and reactor temperatures even in dusty environments [44]. Likewise, arc instability is diagnosed using Hall-effect current sensors [33]. To regulate electrode movement and stabilize arc behavior, fuzzy PID controllers have been developed [34]. Additionally, enthalpy probes are used for diagnosing thermal plasma characteristics [45]. Advanced optical diagnostic techniques have also been proposed for estimating key plasma parameters in arc plasma systems [32]. In these developments, several optical parameters such as optical depth, frame rate, and broadband light sources are considered for estimating plasma parameters under varying operating conditions. Additionally, a high-power LC circuit has been developed to generate arc plasma using argon gas [46]. Producing high-quality, porosity-free welds is a critical requirement in arc welding; therefore, micro-vision cameras and high-dynamic-range (HDR) imaging systems are employed to monitor weld quality, detect porosity, and evaluate weld joint integrity.

Similarly, a range of non-invasive sensing techniques and

probes are employed to diagnose the presence of fault events in non-thermal plasma systems. Among these, the Langmuir probe is one of the most widely used diagnostic tools for non-equilibrium plasma analysis [34]. The Langmuir probe and its modified variants are commonly utilized to measure key plasma parameters, including ion density and ion temperature. Fault detection instrumentation techniques, such as colorimetric probes and thermopile sensors, are used to measure energy fluxes in plasma environments [41]. Additionally, OES is used to diagnose arcing effects and discharge non-uniformity in DBD plasmas. These real-time issues are further analyzed using current and voltage sensor measurements, enabling comprehensive diagnosis of plasma operating conditions. Plasma sources are also utilized to characterize various plasma-based processes, such as DBD plasma, which functions as an actuator

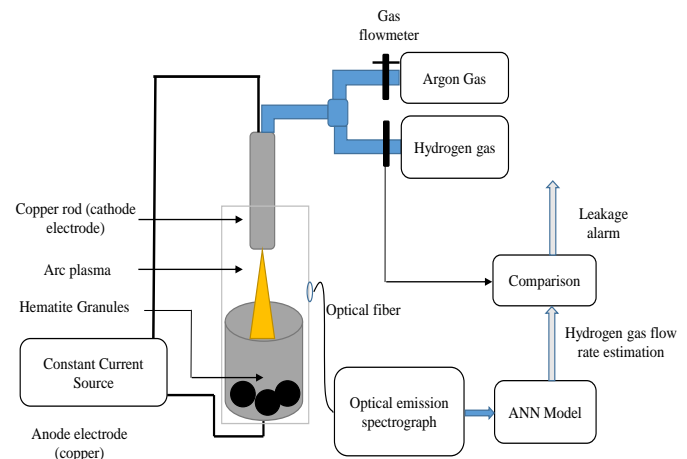


Fig. 5. The experimental setup is embedded with an OES system to estimate the gas flow rate from the emission spectra of reactive species and to detect gas leakage during arc plasma operation [47].

TABLE II
IDENTIFICATION OF FAULT EVENTS IN PLASMA PROCESSES THROUGH SENSOR AND PROBE MEASUREMENTS

Plasma processes	Types of plasma	Fault events	Sensors and probes	Ref.
Arc welding	T	To monitor the dynamic behavior of the plasma flume during arc welding.	A high-thermal-conductivity, three-channel copper array probe was developed to capture welding conditions under high heat-flux environments and to monitor arc fluctuations.	2025 [29]
Metal active gas (MAG) arc welding	T	Weld quality monitoring from porosity and impurities deposition	An acoustic sensing system was developed for weld quality monitoring, where weld quality is classified based on the welding fluctuations sound.	2024 [30]
Transferred arc plasma (TAP)	T	To understand the arcing sound and intensity variation of plasma glow during smelting of mineral ores.	Acoustic and optical sensors are utilized, and the acquired signals are correlated to study arc fluctuations arising from arcing sounds and plasma glow variations.	2023 [19]
Arc welding	T	Real-time quality monitoring of ultra-thin sheet edge welding	MA micro-vision sensing system is deployed for weld quality classification using machine learning algorithms.	2022 [31]
Arc plasma	T	To estimate ion temperature and ion density.	An optical emission spectroscopy (OES) system is positioned near the reactor to capture plasma glow characteristics.	2021 [32]
Arc plasma	T	Diagnosis of arc furnace instability control.	A Hall-effect current sensor is employed to analyze arc fluctuations based on current signal variations.	2018 [33]
Electric arc furnace	T	To control electrode regulation during the smelting process.	A fuzzy PID controller is developed to regulate anode electrode movement.	2015 [34]
DC electric arc furnace	T	To monitor arc fluctuation during the smelting process.	An acoustic monitoring system is embedded near the reactor to record arc fluctuation sounds for assessing arc stability conditions.	2019 [35]
Industrial semiconductor plasma processing	NT	To measure electron-density uniformity during real-time wafer processing.	An electrode-embedded flat-cutoff array sensor has been developed for plasma diagnostics.	2022 [36]
Cold Atmospheric Plasma	NT	Real-time diagnostics of cold atmospheric plasma sources.	Optical emission spectroscopy and electro-acoustic emission methods are employed for real-time diagnostics of cold atmospheric plasma sources.	2019 [37]
RF discharge NT plasma	NT	In-situ diagnostics of highly reactive discharges.	An RF Sobolewski probe is developed for ion flux to obtain electron temperature.	2019 [38]
Magnetron sputtering	Hot NT	Diagnosis of thin film properties of sputtering processes.	(i) A quartz crystal microbalance. (ii) A planar Langmuir probe. (iii) A calorimetric (Gardon) probe.	2012 [39]
High-pressure RF capacitive discharge plasma	NT	For measuring the plasma parameters of an RF capacitive discharge in Argon under atmospheric-pressure conditions.	Resonant near-field microwave probing is developed for contactless diagnostics of high-pressure plasma.	2012 [40]
Low-pressure RF discharge plasma	NT	To measure energy fluxes of confined plasma.	A calorimetric probe and a thermopile sensor are developed to measure energy fluxes.	2010 [41]
Industrial non-thermal plasma	NT	Monitoring and control of industrial plasma processes.	Quantum cascade lasers are developed for mid-infrared absorption spectroscopy applications.	2009 [42]

* T: Thermal plasma, NT: Non-thermal plasma

for monitoring and actively controlling vehicle buffeting noise [49]. Additionally, lasers and fiber-based infrared sensors are used to monitor industrial plasma processes [42]. Atmospheric plasma jets are extensively used in wound-healing applications; however, variations in jet length can adversely affect treatment uniformity and diagnostic accuracy. As a result, various control strategies are implemented to maintain a stable and uniform plasma jet. Therefore, early detection of fault events using sensor- and probe-based diagnostic techniques is crucial for ensuring the reliable and continuous operation of

plasma processes. A comprehensive summary of sensors and probe techniques employed for fault detection in thermal and non-thermal plasma processes is presented in Table II.

IV. SIGNAL PROCESSING TECHNIQUES ON PLASMA DIAGNOSTICS

Information acquired from sensors and probes is typically represented as one-dimensional signals, which are processed using signal processing techniques to diagnose fault events in plasma processes. Techniques such as time-series analy-

sis, sequential data analysis, frequency-domain analysis, and time–frequency analysis are commonly applied to interpret sensor signals, along with various signal transformation methods for effective event characterization. Hall-effect sensors, current sensors, position sensors, voltage sensors, and gas sensors are widely employed in plasma reactors, particularly in arc plasma systems [50]. Initially, Hall-effect current sensors were extensively used to measure the AC in arc plasma reactors. However, with the increasing adoption of DC plasma reactors, arc current in thermal and arc plasma systems is commonly acquired through 4–20 mA serial communication at a high sampling rate, allowing for effective monitoring of arc fluctuations. However, in the recent past, the integration of acoustic sensors, optical diagnostics, and multi-sensor fusion strategies has substantially advanced fault monitoring and process optimization in plasma-based systems. Signal processing-based diagnostic frameworks have been effectively employed to address critical operational challenges, including arc instability in TAP, welding defect identification in arc welding, voltage flicker phenomenon in plasma torch, electrode position regulation, foaming height estimation during smelting, electrode erosion, and electrode breakage in TAP. The signals acquired from embedded sensing units are systematically decomposed, transformed, and analyzed using time-domain, frequency-domain, and time-frequency-domain techniques to detect, classify, and validate fault events in plasma processes.

The schematic illustrated in Fig. 3 depicts a high-temperature plasma torch reactor integrated with multi-sensing diagnostic techniques for monitoring arc fluctuation. The sensing configuration comprises an acoustic sensor, an optical sensor, and a voltage transducer for acquiring voltage signals. Collectively, these sensors provide critical information for characterizing arc instability and arc-root fluctuation within the plasma torch. High-temperature plasma torches are widely employed in pyrolysis processes; therefore, the integration of multi-sensing diagnostic frameworks for real-time reactor health monitoring significantly enhances process stability, operational reliability, and overall productivity.

An arc plasma reactor developed at Mintek, as shown in

Fig. 4, is used for extractive metallurgy, such as mineral ore reduction and the melting of scrap metals. In this setup, the smelting or melting process occurs inside a graphite crucible that serves as the anode, while the cathode is formed by the plasma torch electrode. During operation, arc instability occurs due to the high slag content in the mineral ore reduction process, resulting in the complete separation of metal and slag, which creates a large impedance gradient. To mitigate such instabilities, arc fluctuation is monitored using sensors installed around the reactor. For accurate diagnosis of arc instability, multiple sensors are embedded around the setup to monitor the smelting operation. Arcing sound is generated during operation, caused by arc fluctuations. To capture this sound, a microphone is embedded near the reactor. Similarly, impedance variation due to slag content is monitored through voltage measurements, and plasma glow intensity variations are recorded using an optical sensor.

A dielectric barrier discharge plasma actuator (DBD-PA) is used to examine the vehicle buffeting noise generated from wind tunnel test under the influence of various inflow wind speeds. Different types of actuator layouts are designed using specific parameter combinations, and an interval optimization algorithm is also proposed to identify the actuator configuration that achieves the best equalization control performance under various inflow wind speeds. The experimental results show that, as wind speed increases, both the buffeting noise frequency and the peak sound pressure level increase. The buffeting noise frequency is determined from the fast Fourier transform (FFT), and a correlation study between wind speeds and buffeting noise from the wind tunnel test is also verified. In this examination, a DBD-PA serves as an active flow-control device to mitigate vehicle buffeting noise generated during wind tunnel tests at varying inflow wind speeds.

Similarly, to estimate the gas flow rate into an arc plasma reactor, OES is employed to capture the emission spectra of reactive species (Fig. 5). The acquired spectral signals are pre-processed to reduce noise and extract relevant features, which are subsequently used as inputs to an artificial neural network (ANN) for accurate flow rate estimation. Therefore, the current state of the techniques successfully addresses fault diagnosis in plasma processes and can be further improved with the integration of machine learning techniques to optimize system performance and plasma setups.

In plasma jet devices, characteristic features extracted from signals acquired by embedded sensors provide valuable insights for the design and modification of plasma jet systems [51]. Signals from sensors installed around the reactor are also instrumental in the monitoring of the plasma processing chamber [52]. Furthermore, signal processing techniques facilitate the investigation of reaction mechanisms in atmospheric-pressure plasma processes [53]. However, with the transition from Industry 4.0 to Industry 5.0, the adoption of advanced sensing techniques and the development of novel non-invasive diagnostic systems will become a priority to minimize resource consumption and enhance process efficiency. Similarly, the application of signal processing methods for fault detection and the optimization of plasma process parameters is summarized in Table III.

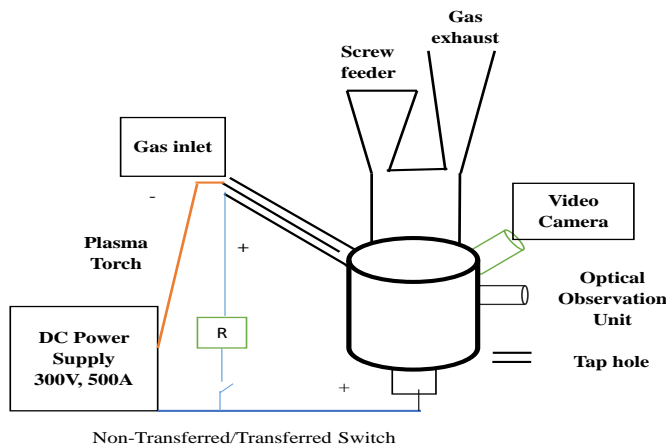


Fig. 6. The Press Reactor, a multipurpose facility developed by SINTEF (Norway), facilitates observation of plasma processes through optical sensing and videographic imaging [48].

TABLE III: Signal processing techniques on plasma diagnostics

Plasma processes	Investigation	Proposed methods	Outcomes	References
Plasma arc welding	To identify depth of penetration and weld quality	Variable mode decomposition (VMD)	VMD modes effectively characterize weld penetration states and process dynamics, thereby improving weld quality	2025 [54]
Arc plasma	Voltage fluctuation due to the instability of the arc	Voltage signal decomposed into time-frequency components using power spectral density and short-time Fourier Transform (STFT)	Instability in arc classified based on the frequency response of the events	2023 [19]
Atmospheric plasma with a glow discharge	The characteristics of the plasma discharge are significantly influenced by variations in the input parameters	Plasma discharge characteristics are determined from the time-domain discharge current signal and the corresponding charge-voltage Lisajous plot.	An efficient and uniform plasma discharge is achieved through optimal control of the input parameters.	2022 [37]
Arc welding	To identify weld defects during the manufacturing of tankers, trucks via arc welding	Qualitative analysis of emission spectra through optical spectroscopy	Emission spectra of characteristic spectral lines are used to identify quality-related events and the presence of porosity.	2022 [55]
Transferred plasma	arc An unexpected loss of the plasma arc in the electric furnace.	Voltage and current signals are analyzed using statistical signal processing techniques along with machine learning methods.	Arc loss events are predicted, and corresponding operational measures for corrective action are developed.	2021 [56]
Arc welding	Welding defects due to impurities and porosity	The arc current signal is processed, and a transfer learning-based method is applied to classify welding current patterns.	Classification algorithms are utilized to identify operating zones from extracted feature representations.	2021 [57]
Ladle furnace	Temperature estimation of molten steel to avoid tapping issues	A hybrid prediction model is used along with the cuckoo algorithm and a neural network to analyze molten temperature data.	Tapping condition is determined from molten temperature using proposed method	2021 [58]
Transferred plasma	arc To estimate gas flow-rate, to accommodate the failure of the mass flow meter	Features of the spectral data fed to the neural network model	A soft sensor is proposed to estimate the gas flow rate from the emission spectra of excited species during the smelting process.	2020 [47]
Plasma arc discharge	To estimate the electrode gap during arcing condition	A Hall effect-based current sensor is used to capture the current signal, which is subsequently analyzed to understand the arcing condition	The submerged plasma arc discharge in water is continuously monitored from the adopted technique.	2020 [59]

Plasma processes	Investigation	Proposed methods	Outcomes	References
Cold atmospheric plasma	Abnormality diagnostics of cold atmospheric plasma (CAP) sources	Statistical analysis of optical emission spectra and electro-acoustic emission lines are performed, and a machine learning model is proposed.	Rotational and vibrational temperatures, along with substrate characteristics, are estimated.	2019 [60]
Electric arc furnace	Arc instability during smelting operation	Signals acquired from the current and voltage sensors are diagnosed to identify arc instability conditions	Dynamic optimization software is created to control arc instability	2019 [61]
DC Non-transferred arc plasma	Current fluctuations inside the furnace during steel-making	Auto-correlation analysis is performed on current and voltage signals.	Auto-correlation coefficients of current and voltage signals, along with the frequency responses of the fluctuations, are utilized to optimize operating parameters.	2017 [62]
Arc Furnaces and Ladle Furnaces	Arc current varies with changes in electrode position.	Current and voltage signals are analyzed using signal processing techniques.	A control system for automatic electrode regulation is developed based on operating current variations.	2016 [63]
Arc plasma	Monitoring hydrogen plasma reduction process	The spectral lines obtained from optical emission spectroscopy are analyzed.	Reduction of oxides monitored through Na and D emission lines	2016 [64]
Electric arc furnace	To estimate the current and voltage behavior during operation	Statistical features of voltage and current signals are used as input to an Extreme Learning Machine for analysis	The proposed model evaluates stability behavior of arc in an efficient way	2015 [65]
Electric arc furnace	Electric arc furnace (EAF) electrodes motion control system to react to tapping requirement	Electrical signal, temperature rating from thermocouple, and emission lines of excited species are analyzed	Optimized electrode motion control is developed from the feedback signals	2015 [66]
DC Non-transferred arc	Diagnosis of arc root dynamics and voltage instability	Voltage waveform of arc is analyzed to evaluate arc root dynamics	Arc stability and instability characteristics are addressed	2015 [67]
Electric arc furnace	To control the electrode regulator system of the electric arc furnace	A fuzzy PID controller was proposed to minimize errors arising from system identification.	Designed controller reduces the nonlinearity effect in the system	2015 [34]
Arc welding	To determine the quality of a weld joint in arc welding.	The operating parameters selected for this study include welding current, welding speed, gas flow rate, and welding gun angle.	A neural network algorithm is proposed to predict weld penetration depth and optimize operating parameters.	2013 [68]
Plasma spray process	To control plasma spray coating	Statistical features of the operating parameters are extracted and input to an artificial neural network (ANN) algorithm proposed for optimizing control parameters.	Operating parameters of the spray plasma is optimized	2013 [69]

Plasma processes	Investigation	Proposed methods	Outcomes	References
Electric arc furnace	To reduce controllable losses during the melting operation	An artificial neural network (ANN) is proposed, and a simulated annealing algorithm is employed to optimize production losses.	Operation loss is minimized and energy consumption is optimized	2013 [68]
Plasma etch equipment	Fault detection and classification in plasma etch processing	The proposed framework integrates a modular neural network with Dempster–Shafer theory to effectively address uncertainties in the system.	Classification of etch processes into acceptable and defective categories is performed using features derived from the operating parameters.	2011 [70]
Dielectric barrier discharge	Identification of reaction mechanism of atmospheric pressure gaseous discharges	The study is conducted using spectral signals of OES, acoustic, and electrical signals	The processing parameters are optimized to determine the reaction mechanism during discharging condition	2011 [53]
Electric arc furnace	Random characteristics of voltage and current during smelting operation	Adaptive neuro-fuzzy inference systems are implemented to facilitate dynamic reconstruction of the nonlinear v–i characteristics.	An optimized process condition is developed	2011 [71]
Electric arc furnace	Estimation of Slag Foaming Height during smelting operation	Fast Fourier transform (FFT) of current and voltage signals is used with the least mean square (LMS) algorithm	Proposed method accurately estimates forming height during smelting	2010 [72]
Plasma etching	In-situ process monitoring in the fabrication of semiconductor wafers	Sigma matching method is proposed along with the spectral response of excited species captured from OES	Process faults detected during real-time diagnosis condition	2010 [73]
Non-equilibrium plasma for material deposition	Diagnosis of plasma processing equipment inside material deposition chamber	Wavelet transform and neural network algorithm are used	Both Discrete Wavelet Transform and Continuous Wavelet Transform are compared to identify plasma faults during operation	2009 [52]
IC-OES	Identification of spectral lines in groups	Identification of spectral lines into soft lines and hard lines are done using an ANN algorithm	Useful for the classification of emission lines to determine the role of emission lines in material characterization through IC-OES	2003 [74]
Arc furnace	Monitoring of electrode breakage	Arc fluctuation and features of the electrical signal are analyzed	The statistical analysis of electrical signals is useful to determine the degradation of electrodes inside the furnace.	2002 [75]

* *T*: Thermal plasma, *NT*: Non-thermal plasma, *IC-OES*: Inductively Coupled Plasma-Atomic Emission Spectroscopy

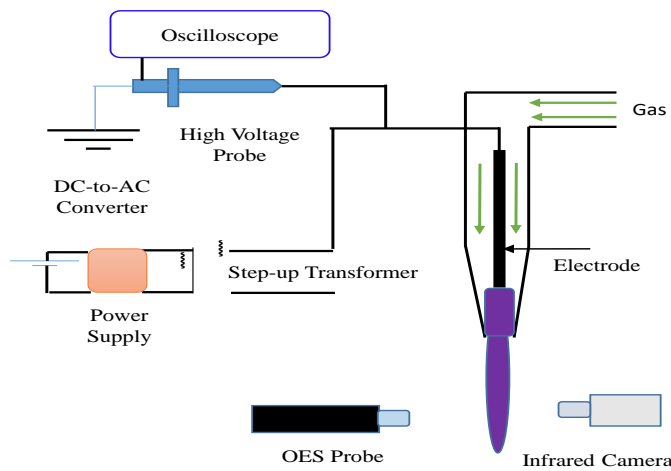


Fig. 7. An OES and an infrared camera are used to monitor plume fluctuations in a non-thermal plasma torch [23].

V. IMAGE PROCESSING TECHNIQUES FOR PLASMA DIAGNOSTICS

Image processing techniques play a significant role in diagnosing fault events in plasma processes and setups, particularly in classifying operational states, detecting anomalies, and analyzing plasma glow characteristics. Advances in camera technologies, such as high-dynamic-range (HDR) cameras and micro-vision cameras with high frame-rate capabilities, have become instrumental for accurate and real-time fault detection in plasma systems. A multi-purpose industrial smelting setup equipped with both signal and image sensors was used to diagnose faults during smelting operations, as illustrated in Fig. 6. Data captured from video cameras, current sensors, and voltage sensors are correlated over time to monitor event occurrences in the plasma process. In this setup, arc fluctuations are tracked using video cameras to capture variations in operating parameters. Similarly, infrared cameras are utilized to monitor arc fluctuations in the plasma torch, as depicted in Fig. 7. In Fig. 7, arc fluctuations are monitored using an infrared camera, an optical emission spectroscopy (OES) probe, and a high-voltage probe. The OES probe provides spectral information to track intensity variation of reactive species, while the high-voltage probe captures high-sample-rate voltage signals. The infrared camera monitors arc dynamics at the anode and cathode roots, including phenomena occurring beyond the visible spectral range. Collectively, the information obtained from these multi-sensing techniques enables comprehensive fault diagnosis and analysis of the plasma setup.

In the thermal plasma domain, image processing techniques have been employed to detect plasma spray jet instabilities [76] and to perform microstructural analysis of thermal barrier coatings [77]. High-dynamic-range (HDR) cameras have also been utilized for weld defect classification in arc welding applications, leveraging convolutional neural network (CNN) based transfer learning approaches [57], [54], [29].

Similarly, in non-thermal plasma processes, image processing techniques and deep learning models have been extensively applied to quantify the erosion of volumetrically featured aluminum foam under ion bombardment [78]. These techniques are also employed for plasma discharge pattern recognition [79], identification of irregular plasma structures [80], and analysis of the influence of input parameters on discharge characteristics [37]. Over the past decade, event detection using image processing integrated with deep learning (DL) and machine learning (ML) techniques has gained significant importance in fault diagnosis, while also enhancing plasma process quality. Image processing methods such as image segmentation and object detection, combined with ML and DL algorithms, are widely applied in industrial plasma processes for fault classification and process optimization. A summary of image processing applications for detecting and monitoring fault events in plasma systems is provided in Table IV.

VI. PERSPECTIVES AND FUTURE DIRECTIONS

This review article focuses on monitoring and fault diagnosis techniques applied to industrial plasma processes. Plasma technologies have versatile applications across various industrial sectors and societal needs. The rapid advancement of plasma science and technology has significantly contributed to improvements in manufacturing, energy production, environmental management, and overall product quality, ultimately enhancing both industrial

efficiency and human livelihood. Therefore, addressing challenges in plasma processing is critical not only for resolving operational issues in plasma-based technologies but also for improving the productivity and efficiency of plasma systems. This section provides a comprehensive overview of the techniques developed and applied for fault monitoring and diagnosis in industrial plasma processes.

- 1) Sensors and probe-based techniques have played a critical role in addressing challenges in plasma processing and detecting fault events in plasma setups. Early diagnostic methods were largely limited to invasive probes and interferometry techniques. However, with the rapid advancement of information and sensing technologies, traditional instrumentation and probes are increasingly being complemented or replaced by micro-vision imaging cameras, high-frame-rate photography, high-resolution spectroscopy, acoustic sensors, and other advanced diagnostic tools. Therefore, it is essential to integrate advanced sensing techniques into plasma reactors and setups as a primary step for capturing process information. Such information may take the form of signals, images, three-dimensional reconstructions, or other data modalities.
- 2) Researchers and industry experts apply signal processing techniques to monitor plasma processes and diagnose fault events during operation. Signals acquired from various sensors, probes, and both invasive and non-invasive diagnostic systems are preprocessed to reduce noise using filtering and transformation methods such as continuous wavelet transform (CWT), discrete wavelet transform (DWT), and power spectral density (PSD) analysis. In the reported studies [19], [81], [82], current, voltage, and acoustic signals were captured at a sampling frequency of 20 kHz. Due to the presence of high-frequency noise components, the signals were preprocessed using the tunable-Q wavelet transform (TQWT). The denoised and preprocessed signals were subsequently used to train machine learning models, including neural networks and extreme learning machines, for predicting and classifying fault events in plasma processes. In addition to applying signal processing techniques to reduce noise in captured signals, it is equally important to periodically calibrate sophisticated instrumentation used for monitoring and fault detection to ensure accurate plasma process measurements.
- 3) Advanced signal processing methods and algorithms are employed to distinguish noise from genuine faults in electrical and mechanical systems, thereby improving fault diagnosis [83], [84], [85], [86], [87], [88]. Recent advancements in signal processing and computational capabilities have further enabled fault event detection using machine learning and deep learning approaches [56], [30].
- 4) In non-thermal plasma setups, optical emission spectroscopy (OES) has been used to detect event occurrences by analyzing the spectral characteristics of reactive species. Similarly, ion energy analyzers are used to monitor the plasma processing chamber, and computed tomography (CT) techniques are also applied to investigate variations in plasma phenomena under changing control parameters by reconstructing the plasma structure within the confined chamber. However, plasma processes are inherently complex and dynamic due to the concurrent physicochemical reactions that occur. Consequently, fault diagnosis in plasma systems extends beyond signal processing methods and increasingly relies on image processing techniques for comprehensive monitoring and analysis.
- 5) Image processing techniques play a vital role in event detection during plasma processing. High-speed cameras are used to monitor electrode erosion in smelting operations. Both high-speed and high-dynamic-range (HDR) imaging systems have demonstrated significant potential in thermal plasma setups for detecting arc instabilities and unexpected arc loss within the furnace. Since electrode erosion can ultimately lead to electrode breakage and pose operational hazards, early detection through image-based monitoring is critical to preventing adverse outcomes during plasma operations. High-speed cameras are also employed to observe arc instabilities caused by arc fluctuations, enabling clear differentiation between stable and unstable plasma operation [76]. Image processing techniques play a significant role in the microstructural analysis of thermal barrier coating surfaces [77]. Recently, computed tomography (CT) methods have been applied to reconstruct three-dimensional (3D) images of inductively coupled plasma (ICP) modes [89]. Additionally, plasma discharge patterns can be visualized using high-speed cameras under varying current and voltage conditions [37]. A summary of reported applications of image processing methods for fault diagnosis in plasma processes is presented in Table IV.

TABLE IV: Image processing techniques for plasma diagnostics

Plasma processes	Investigation	Proposed methods	Outcomes	References
Plasma arc welding	To identify depth of penetration and weld quality	Analysis of weld quality images is performed using continuous wavelet transform (CWT).	Weld quality is improved by identifying penetration states and operational modes.	2025 [54]
Gliding arc	Arc fluctuation	High frame rate images are captured to analysis arc fluctuation	Visual information of gliding arc utilized for processing material	2024 [90]
Electric arc plasma	To identify leakage of gas during operation and interpret failure of current sensor	Images captured under different operating conditions are used to train a deep learning model to identify the operating conditions	Proposed work act as a soft sensor to classify operating conditions, can be accommodated when current sensor fails or leakage of injected gas into the reactor	2023 [81]
Arc welding	Real-time quality monitoring of ultra-thin sheet edge welding	Real-time welding images are captured using a micro-vision sensing camera and analyzed with a support vector machine (SVM)-based swarm optimization combined with a computationally inexpensive floating selection (SOCIFS-SVM) algorithm, enabling the implementation of an online monitoring framework.	A real-time framework was developed to detect defects in ultra-thin sheet edge welding, enabling implementation of online closed-loop quality control	2022 [31]
Thermal spray process	Instabilities and fluctuations of the plasma jet during thermal spray coating	High-frame rate images of the plasma jet are acquired and processed using the inverse Abel transform.	The influence of the particles on the plasma jet originating from the cascaded triple arc plasma generator is identified	2022 [76]
Thermal plasma spray	Micro structural analysis of thermal barrier coating	Image segmentation of splats is performed, and enhanced sintering of air plasma-sprayed thermal barrier coatings is analyzed through the segmented images.	2021 [77]	
Arc welding	Identification and classification of weld defects	CNN-based transfer learning is used for automated weld defect detection and classification from radiography images.	Proposed work efficiently detects weld defects and is helpful in real-time monitoring	2021 [57]
Plasma jet	Plasma jet length classification for variation of operating parameters	Tiny plasma jets are classified using a classification algorithm from the visual images of the flume	The applied methodology facilitates the advancement of cold atmospheric plasma jet technology, offering substantial opportunities in biomedical applications.	2021 [36]
Non-thermal pulse plasma	To monitor temperature variation pulse plasma flows	Pulsed plasma generated in IPU-30 reactors was diagnosed using high-frame rate visible imaging with a Phantom VEO710S fast camera.	Helpful for pulse plasma diagnosis	2020 [91]
Arc welding	Depth of penetration detection in arc welding	A deep learning model was proposed using features extracted from multi-source sensing images	Visual images of the welding arc are utilized to improve monitoring of the gas tungsten arc welding process and detection of penetration.	2020 [92]
Non-thermal impinging plasma jet	To monitor the impinging effect of the plasma jet	ICCD imaging study was done to identify plasma discharge patterns	Implemented imaging method helpful to identify plasma discharge morphology patterns	2019 [93]
DC Non-Transferred arc plasma	Monitor the dynamical behavior of the plasma torch	High-frame-rate images are captured under different operating conditions, and emission spectroscopic analysis was performed for various anode materials	Spectral data of reactive species acquired through optical emission spectroscopy are used to accurately estimate plasma parameters.	2019 [94]
DC Non-Transferred arc the plasma	Visualization and mechanisms of splashing erosion of electrodes in a DC air arc	A high-definition imaging system was developed to monitor electrode erosion during smelting operations.	This study provides insight into electrode erosion mechanisms and material splashing behavior during smelting operations.	2017 [95]
DC Non-Transferred arc the plasma	To monitor the dynamic behavior of plasma in a DC non-transferred plasma torch.	A high frame rate (fps) camera is used to monitor arc fluctuation	Helps to understand arc root dynamics	2017 [95], [20]

* T: Thermal plasma, NT: Non-thermal plasma

In this study, the authors observed that sensors and probes embedded in plasma setups extensively rely on signal processing techniques to detect and diagnose fault events during operation. Over the past two decades, the combined contributions of sensors, probes, and signal processing methods have played a pivotal role in event diagnosis across various plasma systems. More recently, advancements in camera technologies, information technology, and artificial intelligence have collectively enabled significant improvements in plasma process operations, reducing fault occurrences and enhancing overall system performance. Despite the advancements, the inherent physicochemical reactions and dynamic operating conditions in large-scale plasma processes, such as smelting and thermal barrier coating operations, continue to introduce real-time uncertainties. Consequently, the adoption of automation, artificial intelligence, and the integration of multi-sensing systems is essential to address unresolved operational challenges in industrial plasma setups.

VII. CONCLUSION

This literature review focuses on monitoring and fault diagnosis techniques implemented in industrial plasma processes. Emphasis is placed on the use of sensors and probes for detecting fault events during operation, along with the contribution of signal and image processing techniques for fault diagnosis and validation. The review encompasses a broad range of techniques and methodologies employed across various industrial plasma processes to address real-time operational challenges. The literature survey further emphasizes the role of machine learning and artificial intelligence approaches in optimizing plasma processes and improving overall system performance. The diagnostic techniques discussed, drawn from diverse plasma applications, aim to assist researchers and industrial practitioners in selecting and implementing appropriate diagnostic methods under different operating conditions.

ACKNOWLEDGMENT

All the information presented in this article is based on the research findings reported in the articles. The figures presented schematically are the development work of different industrial plasma processes, and the corresponding articles have been cited.

REFERENCES

- [1] N. Nandkumar, Plasma—the fourth state of matter, *International Journal of Science and Technology Research* 3 (9) (2014) 49–52.
- [2] P. A. Sesotyo, M. Nur, J. E. Suseno, Plasma gasification with municipal solid waste as a method of energy self-sustained for better urban built environment: Modeling and simulation, in: *IOP Conference Series: Earth and Environmental Science*, Vol. 396, 2019, p. 012002.
- [3] P. R. Taylor, S. A. Pirzada, Plasma technology in extractive and process metallurgy, *Mineral Processing and Extractive Metallurgy Review* 12 (2-4) (1993) 257–269.
- [4] M. Punčochář, B. Ruj, P. K. Chatterj, Development of process for disposal of plastic waste using plasma pyrolysis technology and option for energy recovery, *Procedia Engineering* 42 (2012) 420–430.
- [5] E. J. Gildersleeve, S. Sampath, Durability of plasma sprayed thermal barrier coatings with controlled properties part i: For planar disk substrates, *Surface and Coatings Technology* 424 (2021) 127678.
- [6] T. Von Woedtke, S. Reuter, K. Masur, K. D. Weltmann, Plasmas for medicine, *Physics Reports* 530 (4) (2013) 291–320.
- [7] Q. G. Reynolds, Plasma arc extinction events—insights from high-speed photography and modelling, in: *Proc. 30th International Congress on High Speed Imaging and Photonics*, Pretoria, South Africa, 2012, pp. 67–73.
- [8] Z. Duan, J. Heberlein, Arc instabilities in a plasma spray torch, *Journal of Thermal Spray Technology* 11 (2002) 44–51.
- [9] M. Vilotijevic, B. Dacic, D. Bozic, Velocity and texture of a plasma jet created in a plasma torch with fixed minimal arc length, *Plasma Sources Science and Technology* 18 (1) (2009) 015016.
- [10] J. Jang, H. Nishiyama, Discharge study of argon dc arc jet assisted by dbd plasma for metal surface treatment, *IEEE Transactions on Plasma Science* 43 (10) (2015) 3688–3694.
- [11] English patents, No. 4208 of 1878 and No. 2110 of 1879.
- [12] L. Tonks, I. Langmuir, Oscillations in ionized gases, *Physical Review* 33 (2) (1929) 195.
- [13] H. Stansfield, The echelon spectroscopy, its secondary action, and the structure of the green mercury line, *Proceedings of the Physical Society of London* 21 (1) (1907) 822.
- [14] A. Sahoo, S. Tripathy, Development in plasma arc welding process: a review, *Materials Today: Proceedings* 41 (2021) 363–368.
- [15] G. Cantoro, V. Colombo, A. Concetti, E. Ghedini, P. Sanibondi, F. Zinzani, F. Rotundo, S. Dallavalle, M. Vancini, Plasma arc cutting technology: simulation and experiments, in: *Journal of Physics: Conference Series*, Vol. 275, 2011, p. 012008.
- [16] H. A. Gabbar, S. A. Darda, V. Damideh, I. Hassen, M. Aboughaly, D. Lisi, Comparative study of atmospheric pressure dc, rf, and microwave thermal plasma torches for waste to energy applications, *Sustainable Energy Technologies and Assessments* 47 (2021) 101447.
- [17] H. Singh, R. Kumar, C. Prakash, S. Singh, Ha-based coating by plasma spray techniques on titanium alloy for orthopedic applications, *Materials Today: Proceedings* 50 (2022) 612–628.
- [18] Y. Yerlanuly, R. Zhumadilov, B. Nemkayeva, A. B. Uzakbailuly, Z. Beisenbayev, Bakenov, M. Ramazanov, A. Gabdullin, V. V. B. Ng, A. N. Jumabekov, Physical properties of carbon nanowalls synthesized by the icp-pecvd method vs. the growth time, *Scientific Reports* 11 (1) (2021) 19287.
- [19] S. P. Sethi, D. P. Das, S. K. Behera, N. Ray, Instability and fault analysis of arc plasma using advanced signal processing methods, *Review of Scientific Instruments* 94 (10) (2023).
- [20] S. Ghorui, S. H. Sahasrabudhe, P. S. S. Murthy, A. K. Das, N. Venkatramani, Experimental evidence of chaotic behavior in atmospheric pressure arc discharge, *IEEE Transactions on Plasma Science* 28 (1) (2000) 253–260.
- [21] T. Guo, B. Huang, C. Li, Y. Lou, X. Z. Tang, X. Huang, J. Yue, Magnetic sputtering of feni/c bilayer film on sic fibers for effective microwave absorption in the low-frequency region, *Ceramics International* 47 (4) (2021) 5221–5226.
- [22] A. H. Khoja, A. Mazhar, F. Saleem, M. T. Mehran, S. R. Naqvi, M. Anwar, S. Shakir, N. A. S. Amin, M. B. Sajid, Recent developments in catalyst synthesis using dbd plasma for reforming applications, *International Journal of Hydrogen Energy* 46 (29) (2021) 15367–15388.
- [23] Z. Chen, R. Obenchain, R. E. Wirz, Tiny cold atmospheric plasma jet for biomedical applications, *Processes* 9 (2) (2021) 249.
- [24] R. Walden, A. Goswami, L. Scally, G. McGranaghan, P. J. Cullen, S. C. Pillai, Nonthermal plasma technologies for advanced functional material processing and current applications: Opportunities and challenges, *Journal of Environmental Chemical Engineering* (2024) 113541.
- [25] K. H. H. Aziz, H. Miessner, A. Mahyar, S. Mueller, D. Moeller, F. Mustafa, K. M. Omer, Degradation of perfluorosurfactant in aqueous solution using non-thermal plasma generated by nano-second pulse corona discharge reactor, *Arabian Journal of Chemistry* 14 (10) (2021) 103366.
- [26] A. Dascalu, V. Pohoata, K. Shimizu, L. Sirghi, Molecular species generated by surface dielectric barrier discharge micro-plasma in small chambers enclosing atmospheric air and water samples, *Plasma Chemistry and Plasma Processing* 41 (1) (2021) 389–408.
- [27] D. Guo, H. Liu, L. Zhou, J. Xie, C. He, Plasma-activated water production and its application in agriculture, *Journal of the Science of Food and Agriculture* 101 (12) (2021) 4891–4899.
- [28] T. Nitsche, C. Unger, E. Weidner, Plasma catalytic reactors for atmospheric gas conversions, *Chemie Ingenieur Technik* 90 (10) (2018) 1453–1464.
- [29] H. Zhang, L. Yang, Y. Huang, A study on the dynamic behavior of plasma plume in laser deep penetration welding of a304 stainless steel based on three-probe detection, *Measurement* 250 (2025) 117209. doi:https://doi.org/10.1016/j.measurement.2025.117209.
- [30] S. H. Tessema, D. Bismor, R. Wyżgolik, Advanced signal processing techniques for plasma-mag welding process, in: *2024 Signal Processing: Algorithms, Architectures, Arrangements, and Applications (SPA)*, 2024, pp. 188–193.
- [31] Y. Hong, M. Yang, Y. Jiang, D. Du, B. Chang, Real-time quality monitoring of ultrathin sheets edge welding based on microvision sensing and socifs-svm, *IEEE Transactions on Industrial Informatics* 19 (4) (2022) 5506–5516.
- [32] S. Gortschakow, S. Franke, R. Methling, D. Gonzalez, D. Uhrlandt, S. Popov, A. Batrakov, Advanced optical diagnostics for characterization of arc plasmas, *IEEE Transactions on Plasma Science* 49 (9) (2021) 2505–2515.
- [33] A. Vicente, A. Velasco, M. Linares, A. Picon, J. A. Artech, J. A. Sainz, New sensor for electric arc furnaces arc stability control, in: *ICS 2018 - 7th International Congress on Science and Technology of Steelmaking: Challenges of Industry 4.0*, 2018.
- [34] H. C. Hong, Z. Mao, Controller design for electrode regulating system of electric arc furnace, in: *The 27th Chinese Control and Decision Conference (2015 CCDC)*, 2015, pp. 864–867.

- [35] J. J. Burchell, C. Aldrich, J. J. Eksteen, T. R. Niesler, G. T. Jemwa, Acoustic monitoring of plasma arcs in direct current electric arc furnaces, *Metallurgical and Materials Transactions B* 40 (2009) 886–891.
- [36] H. C. Lee, J. H. Kim, Flat wave-cutoff sensor for real-time industrial plasma process monitoring, in: 2022 IEEE International Conference on Plasma Science (ICOPS), 2022, pp. 1–2.
- [37] M. Saman, M. H. Ahmad, Z. Buntat, Experimental analysis of cold plasma with glow discharge mechanism under a variety of input parameters, *IEEE Transactions on Plasma Science* 50 (7) (2022) 2110–2125.
- [38] P. Sezemsky, V. Stranak, J. Kratochvil, M. Cada, R. Hippler, M. Hrabovsky, Z. Hubicka, Modified high frequency probe approach for diagnostics of highly reactive plasma, *Plasma Sources Science and Technology* 28 (11) (2019) 115009.
- [39] K. Harbauer, T. Welzel, K. Ellmer, A combined sensor for the diagnostics of plasma and film properties in magnetron sputtering processes, *Thin Solid Films* 520 (20) (2012) 6429–6433.
- [40] D. V. Yanin, A. V. Kostrov, A. I. Smirnov, M. E. Gushchin, S. V. Korobkov, V. I. Strikovskii, V. V. Gundorin, M. V. Nazarov, Diagnostics of the atmospheric-pressure plasma parameters using the method of near-field microwave sounding, *Technical Physics* 57 (2012) 468–477.
- [41] P. A. Cormier, M. Stahl, A. Thomann, R. Dussart, M. Wolter, N. Semmar, J. Mathias, H. Kersten, On the measurement of energy fluxes in plasmas using a calorimetric probe and a thermopile sensor, *Journal of Physics D: Applied Physics* 43 (46) (2010) 465201.
- [42] F. Hempel, V. Artyushenko, F. Weichbrodt, J. Röpcke, Application of quantum cascade lasers and infrared-fibres for the monitoring and control of industrial plasma processes, in: *Journal of Physics: Conference Series*, Vol. 157, IOP Publishing, 2009, p. 012003.
- [43] Z. Li, F. Liang, P. Zhang, X. Zhou, Instability and dynamic behavior of arc attachments on electrodes and the effect on electrode erosion, *International Journal of Energy* 2 (1), iISSN: 2957-9473 (2023).
- [44] F. Sommer, Modern methods in high temperature calorimetry, *Journal of Thermal Analysis and Calorimetry* 33 (1) (1988) 15–28.
- [45] J. Wang, P. Wang, L. Peng, Analysis of thermal plasma diagnostics based on enthalpy probe system, *Vacuum* 206 (2022) 111530.
- [46] W. I. Yaseen, A. F. Ahmed, D. A. Al-Shakarchi, F. A. H. Mutlak, Development of a high-power Ic circuit for generating arc plasma and diagnostic via optical emission spectroscopy, *Applied Physics A* 128 (2) (2022) 148.
- [47] S. Das, D. P. Das, C. K. Sarangi, B. Bhoi, Estimation of hydrogen flow rate in atmospheric arc-h2 plasma by using artificial neural network, *Neural Computing and Applications* 32 (2020) 1357–1365.
- [48] J. A. Bakken, R. Jensen, B. Monsen, O. Raanes, A. N. Wærnes, Thermal plasma process development in Norway, *Pure and Applied Chemistry* 70 (6) (1998) 1223–1228.
- [49] X. Hu, H. Liang, Y. Zhang, J. Wang, P. Guo, Active control of cavity buffeting noise using a dielectric barrier discharge plasma actuator, *Mechanical Systems and Signal Processing* 208 (2024) 110959.
- [50] N. Denisova, Plasma diagnostics using computed tomography method, *IEEE Transactions on Plasma Science* 37 (4) (2009) 502–512.
- [51] K. M. Ahmed, T. M. Allam, H. A. El-Sayed, H. M. Soliman, S. A. Ward, E. M. Saied, Design, construction and characterization of ac atmospheric pressure air non-thermal plasma jet, *Journal of Fusion Energy* 33 (2014) 627–633.
- [52] B. Kim, S. Kim, Monitoring of plasma processing chamber using ion energy analyser and time series neural network, *Surface Engineering* 26 (3) (2010) 224–228.
- [53] N. O'Connor, Electrical, optical and acoustic diagnostics of atmospheric pressure gas discharges, Ph.D. thesis, Dublin City University (2011).
- [54] D. Zeng, D. Wu, H. Huang, B. Peng, Y. Wei, H. Du, P. Zhang, H. Shi, Q. Lu, X. Cai, Online identification of laser welding penetration through multi-photoelectric decomposition-reconstruction and shifted-windows-based transformer deep learning framework, *Measurement* 247 (2025) 116872. doi:https://doi.org/10.1016/j.measurement.2025.116872.
- [55] J. J. Valdiande, L. Rodriguez-Cobo, A. Cobo, J. Miguel-Lopez-Higuera, J. Mirapeix, Spectroscopic-line monitoring of welding of tanker trucks, *Applied Sciences* 12 (10) (2022) 5022.
- [56] L. D. Rippon, I. Yousef, B. Hosseini, A. Bouchoucha, J.-F. Beaulieu, C. Prévost, M. Ruel, S. Shah, R. B. Gopaluni, Representation learning and predictive classification: Application with an electric arc furnace, *Computers & Chemical Engineering* 150 (2021) 107304.
- [57] S. Kumaresan, K. J. Aultrin, S. S. Kumar, M. D. Anand, Transfer learning with cnn for classification of weld defect, *IEEE Access* 9 (2021) 95097–95108.
- [58] Q. Yang, Y. Fu, J. Zhang, Molten steel temperature prediction using a hybrid model based on information interaction-enhanced cuckoo search, *Neural Computing and Applications* 33 (2021) 6487–6509.
- [59] L. Anjarwati, M. Anwar, Y. Mahardhika, R. Fadhillah, C. H. B. Apri-bowo, T. E. Saraswati, Y. Ayub, Current-voltage monitoring of plasma arc discharge submerged in water for nanoparticles fabrication, in: *AIP Conference Proceedings*, Vol. 2217, 2020.
- [60] D. Gidon, X. Pei, A. D. Bonzanini, D. B. Graves, A. Mesbah, Machine learning for real-time diagnostics of cold atmospheric plasma sources, *IEEE Transactions on Radiation and Plasma Medical Sciences* 3 (5) (2019) 597–605.
- [61] S. Shyamal, C. L. E. Swartz, Real-time energy management for electric arc furnace operation, *Journal of Process Control* 74 (2019) 50–62.
- [62] A. A. Nikolaev, P. G. Tulupov, D. A. Savinov, Statistical analysis of random fluctuations of currents in the electric arc steel-making furnace for different melting techniques, in: 2017 International Conference on Industrial Engineering, Applications and Manufacturing (ICIEAM), IEEE, 2017, pp. 1–7.
- [63] A. A. Nikolaev, P. G. Tulupov, G. V. Astashova, The comparative analysis of electrode control systems of electric arc furnaces and ladle furnaces, in: 2016 2nd International Conference on Industrial Engineering, Applications and Manufacturing (ICIEAM), IEEE, 2016, pp. 1–7.
- [64] S. Das, D. P. Das, P. Rajput, J. Ghosh, B. Bhoi, B. K. Mishra, Monitoring hydrogen plasma reduction of oxides by na d lines, *Plasma Chemistry and Plasma Processing* 36 (2016) 1125–1139.
- [65] S. Ismaeel, A. Miri, A. Sadeghian, D. Chourishi, An extreme learning machine (elm) predictor for electric arc furnaces' vi characteristics, in: 2015 IEEE 2nd International Conference on Cyber Security and Cloud Computing, IEEE, 2015, pp. 329–334.
- [66] K. Iashyna, Synthesis and software implementation of electric arc furnace electrodes motion control system, in: 2015 IEEE 8th International Conference on Intelligent Data Acquisition and Advanced Computing Systems: Technology and Applications (IDAACS), Vol. 1, IEEE, 2015, pp. 125–130.
- [67] S. Ghorui, N. Tiwari, K. C. Meher, A. Jan, A. Bhat, S. N. Sahasrabudhe, Direct probing of anode arc root dynamics and voltage instability in a dc non-transferred arc plasma jet, *Plasma Sources Science and Technology* 24 (6) (2015) 065003.
- [68] R. Sudhakaran, V. Vel Murugan, P. S. Sivasakthivel, M. Balaji, Prediction and optimization of depth of penetration for stainless steel gas tungsten arc welded plates using artificial neural networks and simulated annealing algorithm, *Neural Computing and Applications* 22 (2013) 637–649.
- [69] A. Behera, P. Parida, R. K. Behera, S. C. Mishra, Ann controlled plasma spray process by using industrial waste (2013).
- [70] S. J. Hong, W. Y. Lim, T. Cheong, G. S. May, Fault detection and classification in plasma etch equipment for semiconductor manufacturing diagnostics, *IEEE Transactions on Semiconductor Manufacturing* 25 (1) (2011) 83–93.
- [71] A. Sadeghian, J. D. Lavers, Dynamic reconstruction of nonlinear v-i characteristic in electric arc furnaces using adaptive neuro-fuzzy rule-based networks, *Applied Soft Computing* 11 (1) (2011) 1448–1456.
- [72] J. J. Jeong, S. J. Ban, S. W. Kim, Estimation of slag foaming height from vibration signals in electric arc furnaces, in: *ECTI-CON2010: The 2010 ECTI International Conference on Electrical Engineering/Electronics, Computer, Telecommunications and Information Technology*, 2010, pp. 866–869.
- [73] R. Yang, R. Chen, Real-time plasma process condition sensing and abnormal process detection, *Sensors* 10 (6) (2010) 5703–5723.
- [74] A. Lopez-Moliner, J. Pino, A. Castro, J. R. Castillo, Artificial neural networks applied to the classification of emission lines in inductively coupled plasma-atomic emission spectroscopy, *Analytical Letters* 36 (1) (2003) 245–262.
- [75] J. J. Rodríguez-Andina, J. Fariña, J. Bullón, A. Lorenzo, Microcontroller-based monitoring of electrodes in arc furnaces for silicon production, in: *IEEE 2002 28th Annual Conference of the Industrial Electronics Society. IECON 02*, Vol. 3, IEEE, 2002, pp. 2028–2032.
- [76] K. Bobzin, H. Heinemann, A. O'Brien, Capturing the influence of jet fluctuations on particles in plasma spraying, *Journal of Thermal Spray Technology* 31 (1) (2022) 59–69.
- [77] X. Zhang, A. C. F. Cocks, Y. Okajima, K. Takeno, T. Torigoe, An image-based model for the sintering of air plasma sprayed thermal barrier coatings, *Acta Materialia* 206 (2021) 116649.
- [78] A. Ottaviano, A. Thuppul, J. Hayes, C. Dodson, G. Z. Li, Z. Chen, R. E. Wirz, In situ microscopy for plasma erosion of complex surfaces, *Review of Scientific Instruments* 92 (7) (2021).
- [79] Y. Yang, S. Yang, C. Li, Z. Yu, Recognition of plasma discharge patterns based on cnn and visible images, *IEEE Access* 9 (2021) 67232–67240.

- [80] P. Zhang, L. Sun, L. Qi, H. Yu, On-line quantitative analysis of major elements in phosphate slurry using libs assisted by plasma information from orthogonal directions imaging, *Measurement* 234 (2024) 114827. doi:<https://doi.org/10.1016/j.measurement.2024.114827>.
- [81] S. P. Sethi, D. P. Das, S. K. Behera, N. Ray, Monitoring of arc plasma process parameter using cnn-based deep learning algorithm to accommodate sensor failure, *IEEE Transactions on Plasma Science* 51 (6) (2023) 1434–1445.
- [82] S. P. Sethi, D. P. Das, S. K. Behera, Cathode position detection in a transferred arc plasma using artificial neural network, *IEEE Transactions on Plasma Science* 51 (3) (2023) 913–921. doi:10.1109/TPS.2022.3229199.
- [83] P. Mercorelli, Recent advances in intelligent algorithms for fault detection and diagnosis, *Sensors* 24 (8) (2024) 2656.
- [84] D. Leite, E. Andrade, D. Rativa, A. M. Maciel, Fault detection and diagnosis in industry 4.0: a review on challenges and opportunities, *Sensors (Basel, Switzerland)* 25 (1) (2024) 60.
- [85] P. Mercorelli, Using haar wavelets for fault detection in technical processes, *IFAC-PapersOnLine* 48 (4) (2015) 37–42.
- [86] P. Mercorelli, A fault detection and data reconciliation algorithm in technical processes with the help of haar wavelets packets, *Algorithms* 10 (1) (2017) 13.
- [87] P. Mercorelli, Biorthogonal wavelet trees in the classification of embedded signal classes for intelligent sensors using machine learning applications, *Journal of the Franklin Institute* 344 (6) (2007) 813–829.
- [88] Y. Liu, A. M. Bazzi, A review and comparison of fault detection and diagnosis methods for squirrel-cage induction motors: State of the art, *ISA transactions* 70 (2017) 400–409.
- [89] X. Han, Y. Sun, Y. Gao, J. Zhang, H. Tang, Three-dimensional light intensity distribution reconstruction of argon ion in helicon plasma source, *Measurement* 234 (2024) 114523. doi:<https://doi.org/10.1016/j.measurement.2024.114523>.
- [90] R. Kusano, Y. Kusano, Applications of plasma technologies in recycling processes, *Materials* 17 (7) (2024) 1687.
- [91] A. B. Tazhen, Z. R. Rayimkhanov, M. K. Dosbolayev, T. S. Ramazanov, Generation and diagnostics of pulse plasma flows, *Plasma Physics Reports* 46 (2020) 465–471.
- [92] Y. F. Feng, Z. Chen, D. Wang, J. Chen, Z. Feng, Deepwelding: A deep learning enhanced approach to gtaw using multisource sensing images, *IEEE Transactions on Industrial Informatics* 16 (1) (2019) 465–474.
- [93] E. Simoncelli, A. Stancampiano, M. Boselli, M. Gherardi, V. Colombo, Experimental investigation on the influence of target physical properties on an impinging plasma jet, *Plasma* 2 (3) (2019) 369–379.
- [94] S. Bhattacharya, N. Tiwari, A. Mishra, S. Mitra, G. K. Dey, S. Ghorui, Underwater electrical discharges: temperature, density and basic instability features with different anode materials, *Plasma Chemistry and Plasma Processing* 39 (2019) 1019–1048.
- [95] V. Goyal, G. Ravi, P. Bandyopadhyay, S. Banerjee, V. Yugesh, S. Mukherjee, Study of dynamical behaviour of the plasma in a dc non-transferred plasma torch using fast imaging, *Physics of Plasmas* 24 (3) (2017).