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Chapter 16

DIGITIZATION OF WELDING PROCESSES

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Abstract:

Welding processes offer a unique capability with a wide range of applications in industries. In recent times, welding has established itself as a tool for large scale additive manufacturing. In general, the quality and repeatability assurance for welding and specifically for additive manufacturing necessitates integrating process monitoring techniques with existing welding and additive manufacturing processes. The process-specific signals such as welding current fluctuations, temperature, and acoustic, generated during the welding operations, make them a suitable candidate for digitization. This chapter comprehensively describes the process monitoring techniques relevant to welding and additive manufacturing. Firstly, various sensors used during welding are described for their construction and working. Subsequently, specific applications of the sensors in digitizing the welding processes are presented.

Keywords: Process monitoring; Welding; Additive manufacturing; Digitization; Sensors; Industry 4.0; Digital twin.

1. Introduction

Welding is an intricate and uncertain dynamic process that needs to be controlled and monitored to meet the desired standards. In the recent past, the welding system's complexity has increased due to advancements in power source technologies that lead to taking control of many input parameters to minimize the disturbances and improve the output quality. The welding process as a complex system can be controlled by decomposing the system into a few subprocesses [1]. Each subprocess can be monitored for disturbances, inputs, and outputs, as shown in Fig. 1.

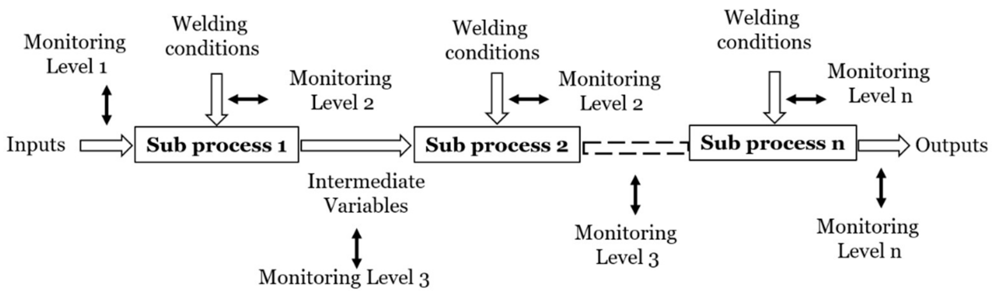

Fig. 1 Effective control and monitoring of welding processes (adapted from [1])

Each subprocess could be monitored for different signals such as welding current and voltage, temperature, arc, type of metal transfer, weld pool, weld seam, weld penetration, wire feed rate, gas flow rate, defects etc. Further, these subprocesses can be grouped into three categories, namely pre-process, in-process and post-process monitoring. Similarly, in additive manufacturing (AM), the process can be efficiently monitored and controlled at three different scales: melt-pool level, single layer, and build level [1]. The first scale monitors the weld pools characteristics and the heat-affected zone (HAZ), which determines the stability of the process and the quality of the component. The second scale monitors single layer characteristics that involve width, thickness, defects, surface pattern, temperature distribution and melting pattern. These factors determine the quality and stability of each layer. The last scale monitors the overall volumetric growth of the component in the build direction and stability of the process. Typically monitoring involves different types of contact and non-contact sensors that convert a process event into a signal.

A variety of sensors for monitoring welding and AM processes is crucial to achieving defect-free welds/components with desirable mechanical properties and metallurgical characteristics. However, as of date, the setup of the sensors involves a lot of manual intervention, making the monitoring activity time-sensitive in addition to it being prone to errors. Modern industries utilize a myriad of processes within the same premises.

With the advent of techniques like machine learning, deep learning, big data analysis etc., the complete process chain must be digitized. A common terminology called 'Digital Twin' has been used for a few years to describe the digitization process. Along the lines of digitization comes the concept of next-generation smart manufacturing, i.e. 'Industry 4.0', which can significantly benefit welding and AM processes. Increased automation through machine-to-machine communication (M2M) and the internet of things (IoT) would improve communication and selfmonitoring. The inclusion of the use of a multi-sensor network in the digitization effort could enhance the thermal management and property homogenization of the produced components, as shown in Fig. 2. In light of the recent developments in sensor technologies and their applications in weld monitoring and control, this chapter presents different process monitoring techniques with specific applications of the sensors for use in welding and AM applications.

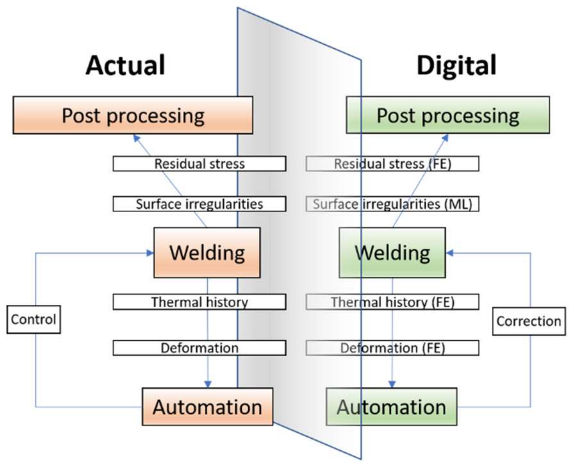

Fig. 2 Concept map of welding digital twin

2. Process Monitoring Techniques

2.1 Electrical Measurements: Welding Current and Voltage

The most critical process parameters are welding current and voltage that determine the welding heat input, weld bead shape, and microstructural properties. For consumable arc welding, the welding current is proportional to wire feed speed, whereas the welding voltage is proportional to arc length. Typically, two types of power source characteristics, namely constant current and constant voltage characteristics, are used for arc welding. Direct and alternating currents are used based on the applications. The actual welding voltage and welding current fluctuate during the consumable electrode welding because the arc resistance continuously changes. At the same time, the molten droplet grows at the electrodes' tip and subsequently detaches. The welding current is measured using probes based on the Hall-effect sensor and shunt resistor.

The current measuring device (e.g., clamp meter) is capable of measuring alternating and direct currents. The clamp meter consists of two clamps made of ferrite iron that are independently copper coiled. There is a slight difference in the working principle of alternate and direct current clamp meter. The AC clamp meter operates as a current transformer, as shown in Fig. 3. The transformer picks up the magnetic flux generated due to the current flowing through a conductor (primary current, I_P). A secondary current (I_S) in the transformer's winding generates due to the electromagnetic induction, which is proportional to the primary current, i.e., I_S=I_P/N, where N is the number of turns on the current transformer winding.

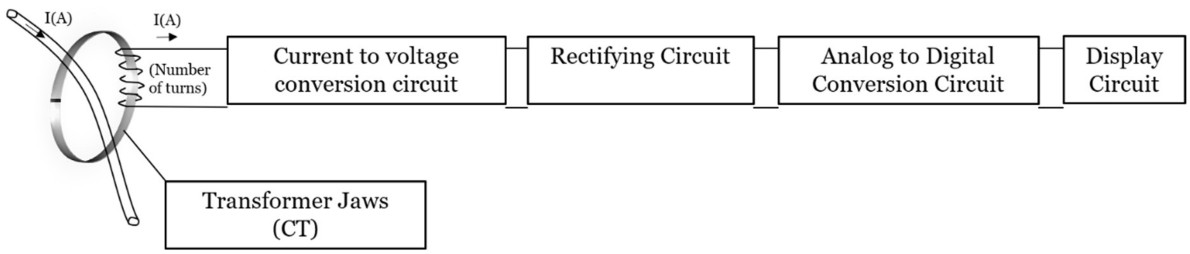

Fig. 3 Clamp meter for alternating current measurement

In the case of direct current, a Hall effect element is used to detect the magnetic flux. A current-carrying conductor placed in a magnetic field generates a voltage perpendicular to both the current and the field. This principle is known as the Hall effect. The Hall Effect element is placed in the gap between the two clamps to detect the current. When the magnetic flux proportional to the current flows in the transformer jaws, the Hall element detects the magnetic flux and generates an output voltage.

The current shunt resistor is based on Ohm's law of resistance. The advantages of this sensor are lower costs compared with other sensing techniques and reliability. The current shunt resistor consists of a resistive element connected between two terminals. Manganin is used as a resistive element material that has properties such as high power, low resistance, and good conductivity. The current shunt resistor is connected in a series connection with the welding equipment, as shown in Fig. 4. The current is allowed to flow through the resistor, causing a drop in voltage across the resistor, which is used to measure the current flow.

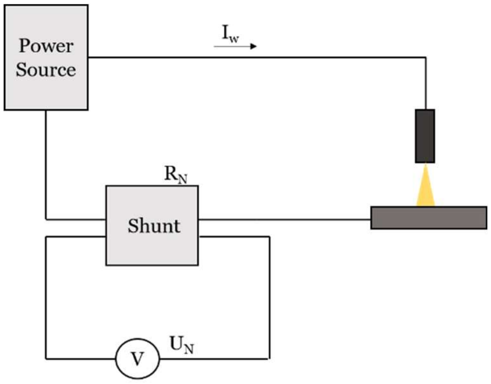

Fig. 4 Operation of a shunt resistor

The welding voltage is measured using a capacitor or resistive type sensors. The welding voltage can be measured at two different locations, either at the output terminal or across the welding torch and workpiece, based on the power source characteristics. The welding voltage should be measured closer to the welding arc, which is not possible in practice. The capacitor type voltage sensor consists of an insulator and two conductors. The insulator is placed between the two conductors in a series connection, as shown in Fig. 5 (A). When the voltage is provided across the conductors, the current will start to flow within the capacitors. The difference in capacitance provides the measured voltage values.

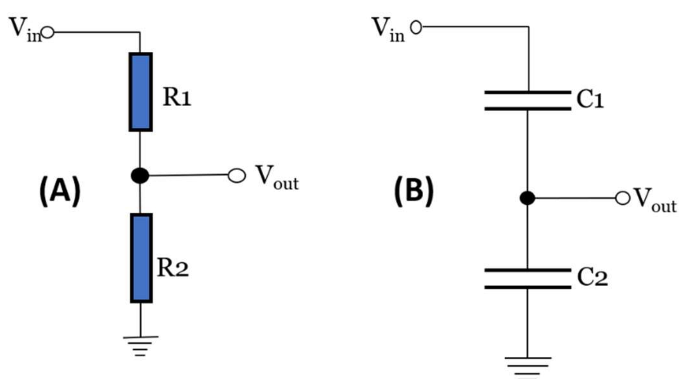

Fig. 5 Voltage sensor (A) Capacitor type, and (B) Resistive type

The resistive type of voltage sensor is of two types: voltage divider and bridge circuit. The voltage divider circuit consists of two resistors, as shown in Fig. 5 (B) where one act as a reference voltage and other act as a sensing element. There are four resistors in the bridge circuit, out of which one resistor acts as a voltage detecting device. The voltage change due to the change in resistance is amplified and measured.

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2.2 Thermal Measurement

Another critical aspect in welding and AM is thermal management, i.e., controlling the temperature that decides the weld's quality. Temperature plays a vital role in the solidification of the material and mechanical properties. Temperature can be measured using various types of sensors that are broadly classified into two categories: contact type and non-contact type sensors, as shown in Fig. 6.

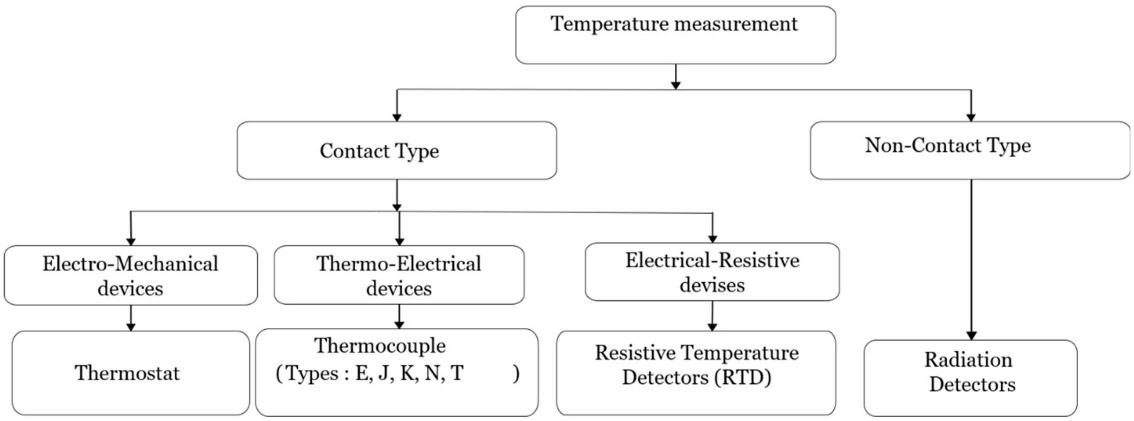

Fig. 6 Classification of temperature measurement techniques

The contact type sensors are further classified into three categories: electro-mechanical, thermo-electrical and electrical-resistive devices. Among the thermo-electrical devices, thermocouples are primarily used to measure welding temperatures ranging from -200°C to 3000°C. The thermocouple consists of two junctions of dissimilar metals, with one junction acting as the reference (cold), while the other is the measuring junction (hot). A difference in temperature among the two junctions leads to a voltage drop, which is used to measure the temperature, as shown in Fig. 7. Several thermocouple material combinations are available based on the range of temperatures, as shown in Table 1. The K type thermocouple is suitable for welding and AM applications that can withstand high temperatures with excellent sensitivity.

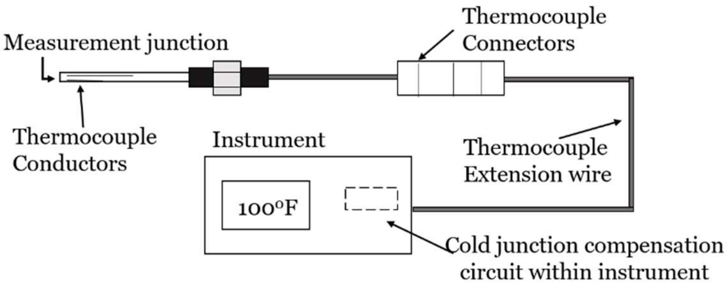

Fig. 7 Thermocouple

Table 1 Standard combination of Thermocouples

Temperature range (°C)	Output (µV/°C)	Standardized letter designation	Material
-262 to 850	15 at 200 °C 60 at 350 °C	T	Copper/Copper-Nickel alloy (constantan)
-19 to 700	26 at 190 °C 63 at 800 °C	J	Iron/Copper-Nickel alloy (constantan)
-268 to 800	68 at 100 °C 81 at 500 °C 77 at 900 °C	E	Nickel-Chromium alloy (chromel)/ Copper-Nickel alloy (constantan)
-250 to 1100	40 from 250 to 1000 °C 35 at 1300 °C	K	Nickel-Chromium alloy (chromel)/Nickel Aluminum alloy (alumel)
0 to 1250	37 at 1000 °C	N	Nickel Chromium Silicon (nicrosil)/ Nickel Silicon Magnesium alloy (nisil)
100 to 1750	5 at 1000 °C	B	Platinum-30% Rhodium/ Platinum-6%Rhodium
0 to 1500	6 from 0 to 100 °C	S	Platinum-10% rhodium/Platinum
0 to 1600	10 at 1000 °C	R	Platinum-13% rhodium/Platinum

The non-contact type temperature sensors use convection and radiation to monitor temperature changes. Radiation detectors are classified into three categories: a) thermal detectors, b) optical pyrometers, and c) photon or quantum detectors. The temperature is measured with an optical pyrometer by comparing the brightness of the emitted source and reference lamp, as shown in Fig. 8. The objective optical lens captures the radiation emitted from the source. The thermal radiation is focused using a lens on to the reference lamp. When the observer changes the rheostat values, the current in the reference lamp and its intensity changes. The current is calibrated on the temperature scale vis-a-vis lamp's filament is not optically distinguished when the filament and

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temperature source's brightness is the same. If the filament is darker than the temperature source's brightness, the source is hotter than the filament and vice-versa.

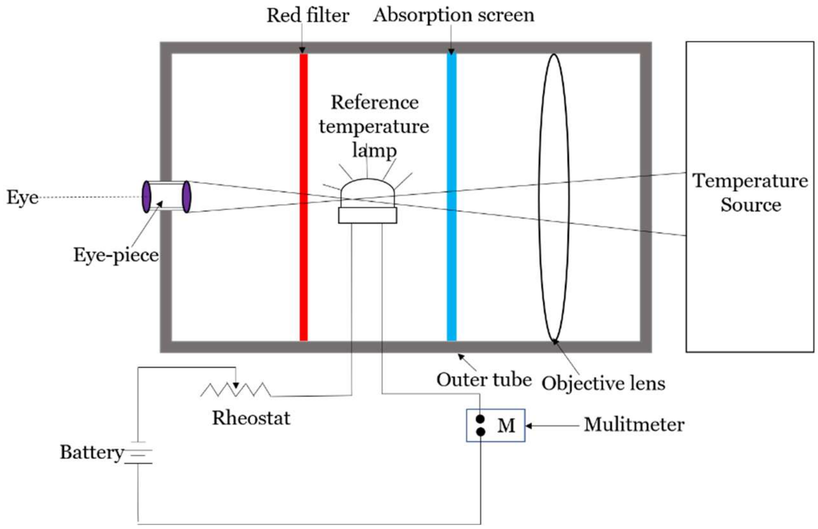

Fig. 8 An optical pyrometer

The thermal detector converts the absorbed electromagnetic radiation into heat energy, causing a rise in detector temperature, which can be sensed by different devices such as a bolometer, thermopile and pyroelectric detectors. Out of these, pyroelectric detectors are commonly used in welding processes. Pyroelectric detectors have a faster response time than bolometers and thermopile. The construction and working principle of a pyroelectric detector is shown in Fig. 9. The sensitive element consists of two electrodes with pyroelectric material such as triglycine sulfate or lithium tantalite. The sensitive element absorbs the object's radiation, causing changes in the surface electric charge on the pyroelectric material. The detector produces an electrical signal proportional to the change rate of charge and is processed by a preamplifier.

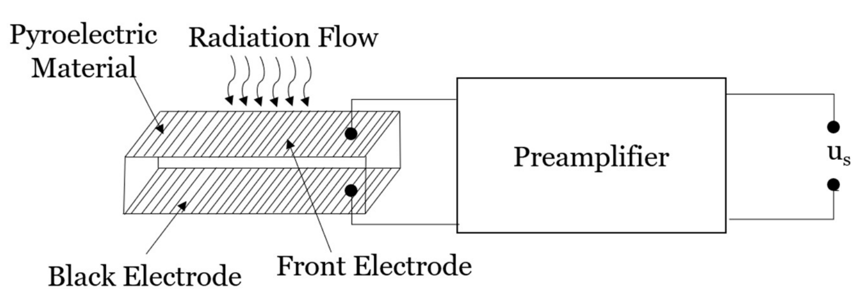

Fig. 9 Construction and working of a pyroelectric detector

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The quantum detectors (photoemissive, photoconductive and photovoltaic) operate on the photo effect, where the electron excitation to conduction states by incident photons is measured. On the other hand, photon detectors capture individual photons' response by releasing or displacing electrical charge carriers. Even though quantum detectors have higher sensitivity than thermal detectors, they are not efficient due to excited electrons' fall to the ground state.

2.3 Optical Measurement

The optical sensors work by sensing light. Optical sensors are typically non-contact that can detect and control various welding parameters such as weld pool, weld seam, and arc length. Fig. 10 represents the typical welding control system using an optical sensor that uses the output to control the welding process.

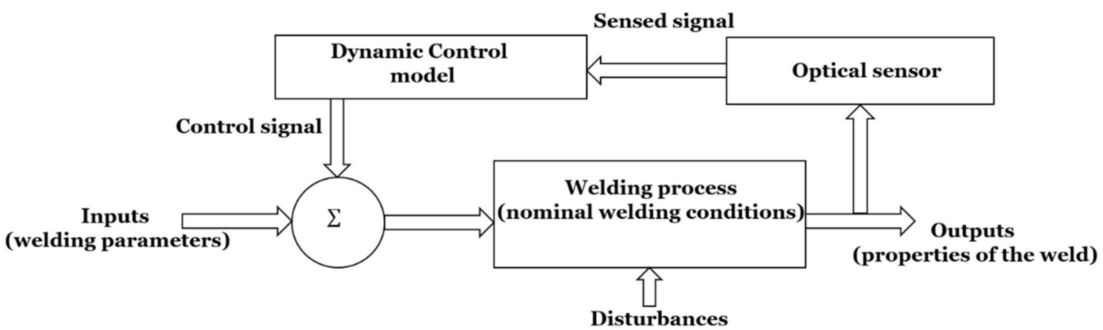

Fig. 10 Optical sensor in a welding control system (adapted from [1])

The commonly deployed sensors in welding processes include electro-optic sensors, charge-couple device (CCD) sensors, complementary metal-oxide-semiconductor (CMOS) sensors, and a high-speed camera. The electro-optic sensor, also called photodetectors, senses light or electromagnetic energy. The photodetectors are made of materials like germanium, silicon, or alloys of indium and antimony or mercury, telluride and cadmium. The operation of these occurs either in photoconductive or photovoltaic mode. The photoconductive detectors absorb photons that elevate electrons, which changes the detector material's conductivity. The photoconductive detector is biased with the load resistor, as shown in Fig. 11 (A). Photovoltaic detectors are also known as photodiodes under no light conditions. Fig. 11 (B) represents the photovoltaic detector operation. These detectors absorb photon to create an electron-hole pair across the p-n junction,

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which produces a photocurrent (without external bias) that charges the capacitor proportionally to the incident radiation.

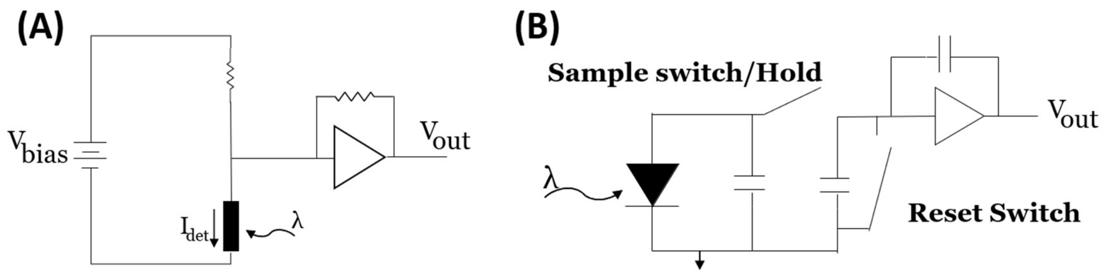

Fig. 11 (A) photoconductive detector, and (B) photovoltaic detector

The CCD sensors are like photodiodes. They are made from a silicon material that is commonly used in digital cameras. The sensitivity range covers both visible light and near-infrared spectrum. The CCD sensor senses the light intensity, which is later captured as an output voltage signal. However, the CCD sensor cannot sense the colour of light, which can be resolved by coating each pixel with colour (red, green, blue) filters and then finding out the missing information. There are three basic techniques used in scanning the images such as point, line and area scanning. The CCD area image sensor uses different architectures based on transfer methods that are classified into four types such as frame transfer (FT), full-frame transfer (FFT), interline transfer (IT) and frame interline transfer (FIT). The difference between these transfer methods is the type of detectors, e.g., metal oxide semiconductors (MOS), photocapacitors, photodiodes, and photocapacitors. In the CCD sensor, the widely used transfer method is either FFT or FT. Each of the different transfer methods follows the same principle of converting the light signal into an output voltage for each pixel in the image array. The CCD imaging sensor operates on a three-step process, as shown in Fig. 12. The first step is exposure, where the light is converted into an electric charge within a pixel. The second step is charge transfer, wherein the charge is moved to the silicon substrate. The final step is to convert the charge to the output voltage and amplify it [1].

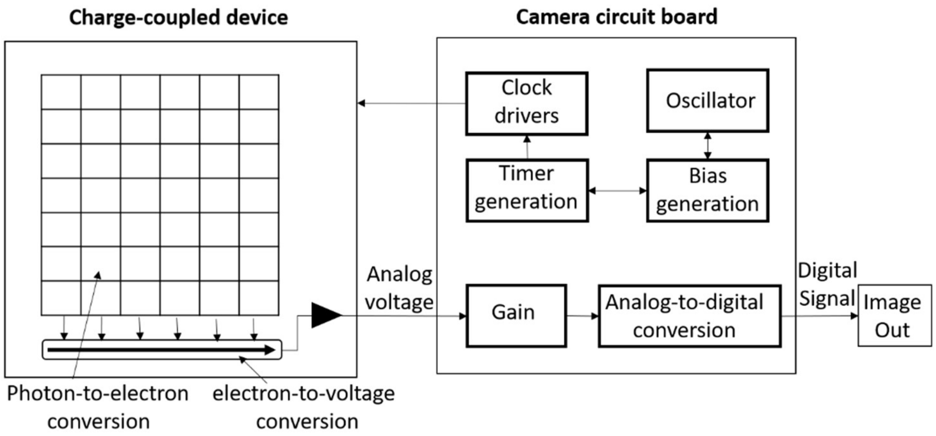

Fig. 12 Working principle of CCD sensor (adapted from [1])

Another essential optical device is a high-speed camera that records slow-motion to study transient phenomena. High-speed cameras can record images up to 250000 frames per second by running the image over a rotating prism or mirror instead of using a shutter, as shown in Fig.13.

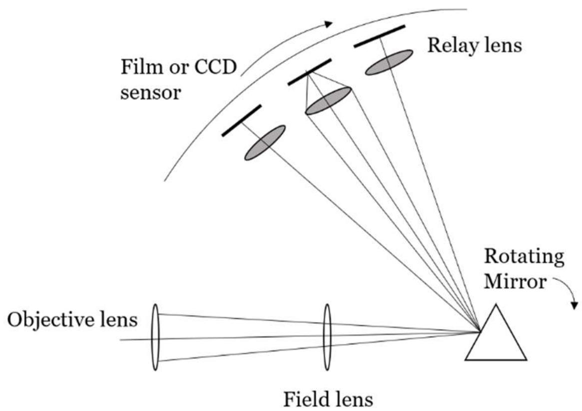

Fig. 13 Operation of a rotating mirror high-speed camera (adapted from [2])

2.4 Acoustic Measurement

Acoustic sensors such as microphones are capable of transforming sound pressure waves into electrical signals. Several factors, like dynamic range, size, sensitivity, bandwidth, and sensitivity, decide the microphone selection for various monitored processes. The microphone senses the pressure variation produced in the air. The sound waves are perceptive to human being between 20 Hz and 20 kHz. The sound waves beyond 20 kHz referred to as ultrasound waves. The ultrasound wave frequency can only travel in a liquid medium efficiently. In welding and AM

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processes, the sound pressure levels (SPL) can predict the behaviour of the arc, type of metal transfer, weld pool, weld defects etc. The SPL is measured in decibels (dB). There are different microphones types, including dynamic microphone (moving coil type and ribbon type), condenser microphone (capacitor), piezoelectric microphone, electret microphone, and resistive microphone. A typical microphone is shown in Fig. 14. Out of these different types of microphones, commonly used are piezoelectric microphones. This microphone consists of the piezoelectric ceramic material on both ends of the electrically conductive electrode. The piezoelectric crystal converts mechanical stresses into electrical charge. In addition, this sensor can record and process the acoustic emission (AE) emitted.

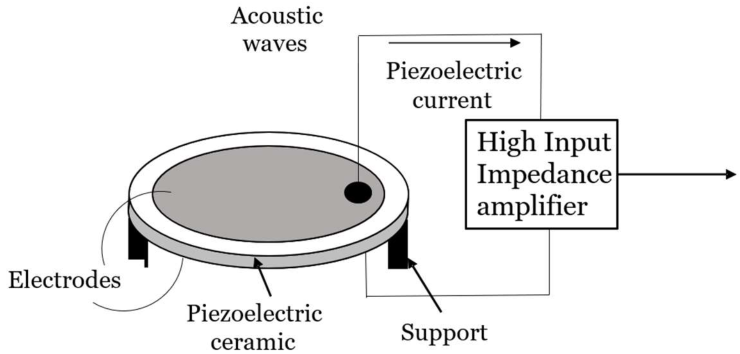

Fig. 14 Piezoelectric microphones

2.5 Displacement and Velocity Measurement

The vibrometer is a non-contact sensor used to measure the displacement and velocity of a moving object. This sensor uses two types of laser source: helium laser and infrared laser, based on the application. The commonly used vibrometer is the single point laser Doppler vibrometer (LDV). The LDV can measure high frequencies with fair amplitude resolution. LDV consists of a laser source, three beam splitters, Mach-Zehnder-interferometer, two detectors, and a lens, as shown in Fig. 15. LDV works on the Doppler Effect along with an interferometer to measure the vibrations on the moving objects. The laser light from the laser source is split by beam splitter (BS1) into a reference beam and object beam. The object beam passes through a beam splitter (BS3) and focused on the moving object with a lens's help. The reflected light (backscattered beam) is diverted to BS2 through BS3 and mixes with the reference beam causing a shift in frequencies. These shifts in frequencies are due to the Doppler-effect. The output optical signal is detected and

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converted to electrical signals using two photodetectors (i.e., PD1 and PD2). Further, these signals are demodulated in terms of displacements and velocities values of the moving object.

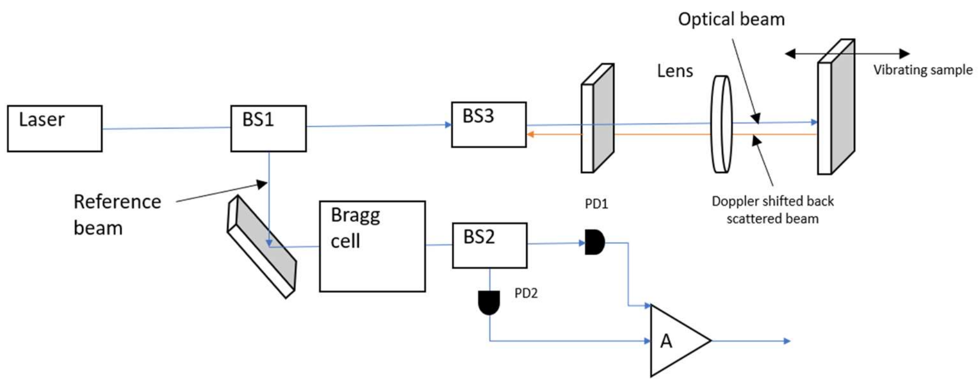

Fig. 15 Laser Doppler vibrometer

2.6 Force Measurement

The dynamometer is a contact type passive transducer that converts mechanical displacements into electrical signals. The dynamometers are commonly used in measuring the force, displacement and pressure acting on the welding tool and base material (BM). A strain gauge-based dynamometer is commonly used in Friction stir welding and resistance welding to measure the forces. The strain gauge consists of elastically deformable material connected to a Wheatstone bridge. When the load is applied to the strain gauge, the wire's length on the strain gauge increases that causes a change in the Wheatstone bridge's resistance. The welding arc pressure is measured by arc pressure sensors that convert the pressure waves to electrical signals amplified with processing circuits. Piezoresistive sensor and piezoelectric sensor are commonly used in measuring the pressure of the welding arc. These pressure sensors consist of a sensitive element to sense the pressure waves and a conversion element to convert the pressure wave into electric signals. The piezoresistive sensor consists of silicon as a piezoresistive element, as shown in Fig. 16. This sensor is connected to the Wheatstone Bridge circuit whenever there is a change in pressure or stress on the silicon element. The resistance of the bridge changes and produces an imbalance in the circuit. On the other hand, the piezoelectric element generates a charge proportional to the input pressure wave's magnitude.

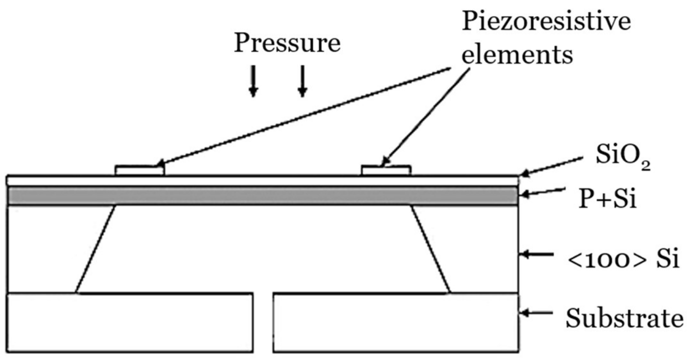

Fig. 16 Piezoresistive sensor

2.7 Electro-Magnetic Field (EMF) Measurement

In welding and wire-based AM, a magnetic field surrounds the current flow direction. This EMF can be captured using different sensors, including gauss meters, webmasters, magnetometers etc. Gaussmeter with Hall effect probe is commonly used to measure the EMF in welding and AM processes. A typical gaussmeter with a Hall-effect probe is shown in Fig. 17. This probe consists of a Hall-effect element, which is connected to an electric circuit and voltmeter. Depending on the intensity of the magnetic field, the voltage varies. The Hall-effect gaussmeter amplifies the output and records the magnetic field's intensity in electric voltage.

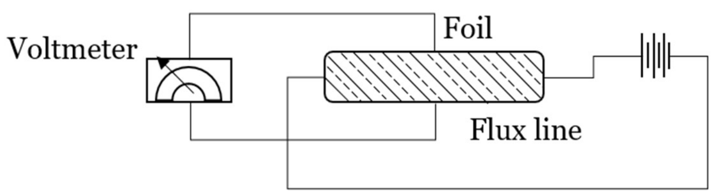

Fig. 17 Hall-effect based gaussmeter

3. Process Monitoring Applications

The process-monitoring technologies mentioned in the previous section have been utilized for various welding processes with wide-ranging applications. Table 2 enlists the different sensors that have been employed for the extraction of welding data with different purposes, depending on the process employed. It is to be noted that the information provided in Table 2 is not exhaustive; instead, it tries to capture the broad spectrum available for the use of sensors in welding and AM.

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This section provides specific examples from literature describing the use of the sensors for measurement of a specific quantity or characteristic in welding and AM processes.

Table 2 Sensors and their applications in monitoring for a variety of welding processes

Sensor/signal	Purpose	Processes						
		Arc welding	FSW	Laser	RSW	USW	Impact welding	AM
Current and Voltage	Welding heat/power	✓		✓	✓			✓
	Melting efficiency	✓						
	Arc stability	✓						✓
	Weld defect detection	✓			✓			
	Dynamic resistance				✓			
	Energy deposition						✓	
Temperature	Thermal cycle	✓	✓	✓	✓			✓
	Arc temperature	✓						
	Weld pool temperature	✓		✓				
	Tool temperature		✓	✓	✓			
	Bead surface temperature	✓	✓					✓
Optical	Arc behavior	✓						✓
	Droplet detachment	✓						✓
	Weld pool monitoring	✓		✓				✓
	Defect detection	✓	✓	✓				✓
	DIC	✓	✓					
	Solidification pattern and Microstructure formation	✓	✓	✓	✓	✓	✓	✓
Acoustic	Process stability	✓						
	Weld defect detection	✓			✓			
Laser Vibrometer	Displacements and vibration velocities		✓		✓	✓		
Dynamometer	Axial force		✓		✓			
Gauss meter	Arc blow effect	✓						
	Health safety to the operator	✓			✓		✓	✓
PDV	Velocity and displacement data						✓	
Pressure	Arc pressure	✓						

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	Time-dependent collision pressure						✓	
(FSW-Friction stir welding, RSW-Resistance spot welding, USW-Ultrasonic spot welding, PDV- Photon Doppler velocimetry, DIC- Digital image correlation)								

3.1 Welding Current and Voltage Measurement

Real-time monitoring of voltage and current has been utilized in various welding processes, including arc welding, laser welding, RSW, impact welding and more recently, in wire and arc additive manufacturing (WAAM). The heat input is related to the current and voltage using Eq. (1) [3, 4]. Eq. (1) is further used to calculate melting efficiency (Eq. (2)), which is essential, as it provides an idea of the amount of energy utilized to form the deposit area (A_d) from the total energy input.

$$HI = \frac{\int V(t)I(t)dt}{S} \tag{1}$$

$$E = \frac{A_d * 100}{0.0854 * (HI)} \tag{2}$$

where HI is the heat input in kJ/mm, $V(t)$ is the instantaneous voltage in V, $I(t)$ is the instantaneous current in A, S is the travel speed in mm/sec, and E is the melting efficiency.

The dynamic welding current and voltage signals are monitored and extracted using a current sensor and data acquisition system (DAQ), respectively. A representative variation of the current and voltage signals is shown in Fig. 18 (A). Moinuddin and Sharma [5] analyzed the current and voltage signals to understand better arc instability under the anti-phase synchronized twin-wire GMAW process. The arc stability is evaluated by analysis of cyclograms (Fig. 18 (B)) and probability density distribution (PDD). The effect of the arc stability correlates with the weld microstructure and shape. The assessment of arc stability can also be conducted using discrete wavelet transformation [6] using quantitative wavelet-energy-entropy (WEE) analysis of the current signals. Fig. 18 (C (i)) represents the wavelet transformation of the current-voltage signal shown in Fig. 18 (A), whereas Fig. 18 (C (ii)) depicts the energy-entropy ratio for different base wavelets.

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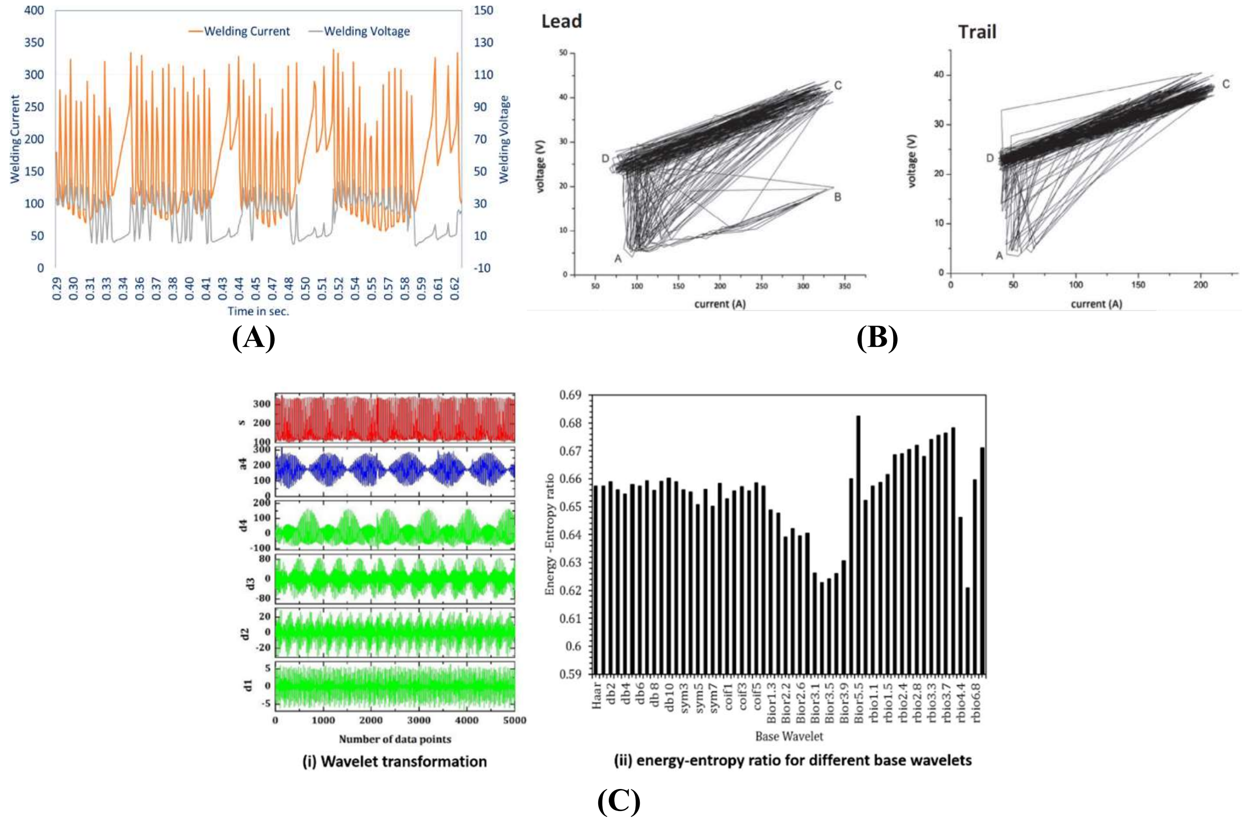

Fig. 18 (A) Typical current-voltage signal in pulsed GMAW [6], (B) cyclograms for stability analysis for a case of twin-wire GMAW [5], and (C) (i) wavelet transformation obtained from the current-voltage in (A), (ii) energy-entropy ratio for different wavelets [6]

The use of current and voltage data for process monitoring goes beyond arc welding for processes like laser welding, RSW, impact welding and even WAAM. Dynamic resistance, a parameter analyzed in RSW process, involves measuring current and voltage signals [7]. In impact welding processes like magnetic pulse welding (MPW), the current signal gives the circuit rise time, which is further used to calculate the parameters like impedance, overall efficiency, etc. [8]. In a recently developed impact welding process viz. vaporizing foil actuator welding (VFAW), the current and voltage signals were analyzed to determine the energy deposition and the process's efficiency [9]. Weld defect detection and evaluation of weld seam quality by detecting current and voltage in the various arc welding process is also prevalent in literature [10-11].

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3.2 Thermal Measurement

Measurement of transient temperature or monitoring the temperature variation during welding is vital for monitoring the quality of the process and production of sound welds. The thermocouples are used to measure the temperature variation in the workpiece's body to obtain the thermal cycle and identify the heat source model parameters based on the welding conditions [12]. The heat source model parameters for different welding processes, e.g., single-wire welding, twin-wire welding [13], square waveform welding [14], need to be adapted for better representation of the process. The heat source models can accurately explain the correlation between welding parameters and weld properties like bead shape and cooling time. The knowledge of cooling rate (obtained experimentally) is essential as it influences the resulting microstructure and, consequently, the mechanical properties of the weld [15]. Thermographic process monitoring, i.e. monitoring the melt pool and the accompanying temperature field, is common for welding processes. Infrared thermography is used to investigate the effects of the oscillation frequency and focal diameter on the weld pool and temperature field [16]. Thermographic videos allow the characterization of the melt pool in terms of the pool attributes (area, width, length) and also the angle of the solidification fronts. Details of temperature sensors employed in laser welding to measure the temperature of molten pool or vapor pool are available in a comprehensive review by You et al. [17]. In addition to weld pool monitoring, infrared sensors are also used for real-time observation of the tool temperature in FSW [18], as shown in Fig. 19. The temperature of the tool pin can be precisely maintained through feedback control.

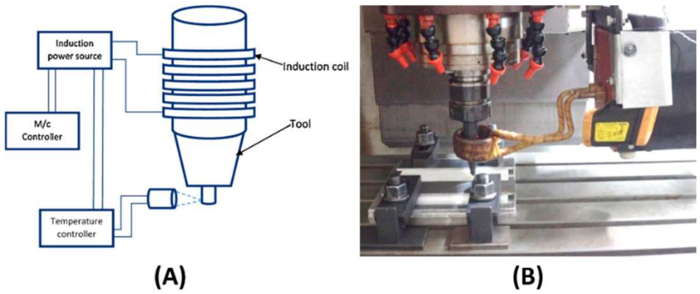

Fig. 19 (A) Schematic of the temperature measurement of tool pin in Induction heated tool assisted FSW, and (B) actual setup [18]

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3.3 Optical Measurement

Optical sensors (CCD and CMOS image sensors) are utilized for a variety of purposes in welding processes, including but not limited to observation of arc behavior, droplet detachment, weld seam tracking, defect detection. Shigeta et al. [19] utilized imaging spectroscopy to investigate the effect of CO_2 mixture in a shielding gas on the metal transfer process in GMAW. They used temperature measurement in the argon plasma and metal plasma regions to observe the plasma characteristics and the dynamic behavior of the droplet. Understanding the arc behavior through high-speed imaging becomes even more critical in multiple-wire welding, where the behavior of one arc influences the other and in turn, enhances or degrades the overall process [20]. The arc images in Fig. 20 depict the arc interactions at various times as a function of the welding current.

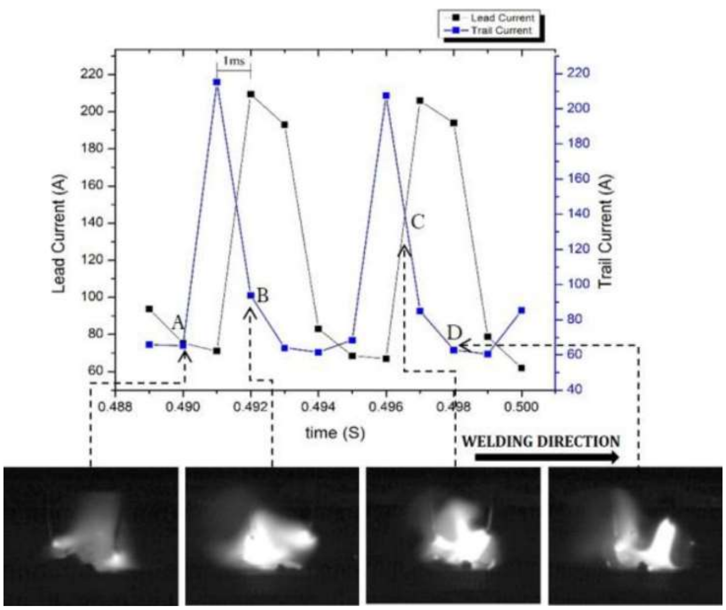

Fig. 20 Variation of arc behavior with current and voltage in twin-wire GMAW [20]

In addition to measuring the temperature distribution of the arc and its behavior, it is also important to observe the droplet formation and detachment. Mamat et al. [21] utilized a two colour temperature measurement method in plasma MIG welding to measure the temperature of the droplet. Based on the temperature measurements, a mechanism to control the droplet temperature can be developed. Additionally, the metal transfer behaviour can also be captured using the shadowgraph method and through colour high-speed video camera observation (colour HSVC). Visual inspection through high-speed imaging is used to understand the arc, droplet, and weld pool's dynamic behaviours, and the same has also been applied to AM. Fig. 21 depicts a typical droplet detachment observed in compulsively constricted wire and arc additive manufacturing (CC-WAAM).

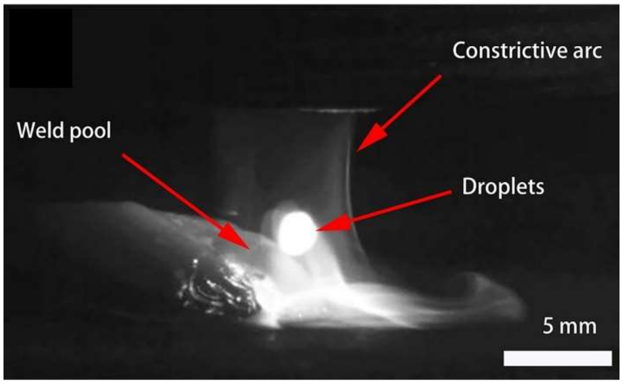

Fig. 21 Experimentally observed droplets and ejected plasma in CC-WAAM [22]

On-line monitoring of the weld pool in arc welding is also conducted by segmentation of the reflected laser lines [23]. The segmentation is combined with image processing algorithms which allows robust and accurate measurement of the weld pool surface geometry. Weld defect detection and classification through a machine vision approach can also be applied in actual production [24]. Another non-contact type optical technique for characterization of weld mechanical properties that has gained increased popularity in the recent decade is DIC. DIC can characterize the different zones such as fusion zone, HAZ and BM of a deposited weld. The experimental set up for DIC is shown in Fig. 22 (A), whereas Fig. 22 (B) presents the strain distribution data used for zone identification. Optical sensors, including photodiodes, high-speed cameras, and spectrometers, have been prevalent in laser welding. Application of these sensors allows detection of vapor plume or plasma reflective laser energy, observation of keyhole and molten pool, defect detection etc. [17].

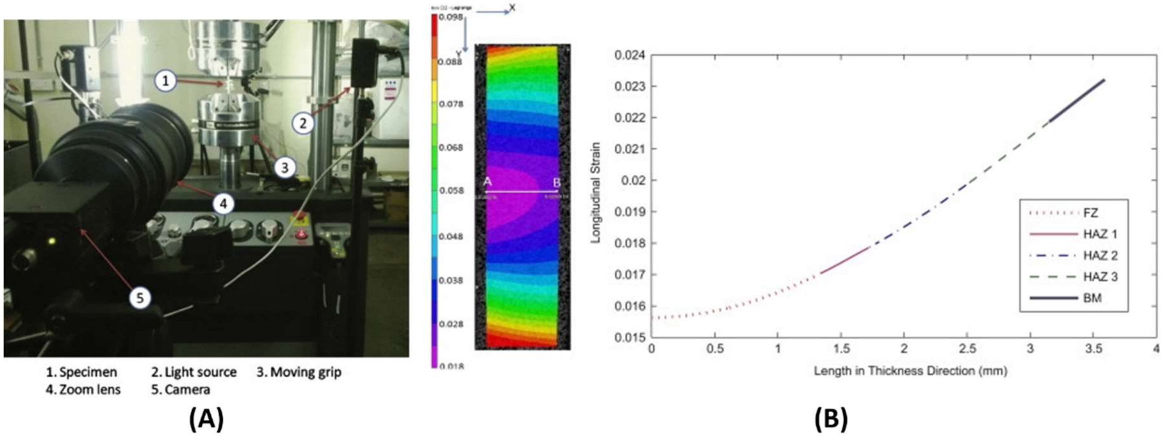

Fig. 22 (A) Experimental set up for DIC, and (B) zone identification using strain distribution [25]

3.4 Acoustic Measurement

For welding and AM processes, there exist different acoustic emission sources at different stages of the process that help monitor the quality of the process and also identify defects, e.g., Pal et al. [26] related the arc sound in GMAW to both the parameters of the process and the quality of the weld. The acquired arc sound signal combined with voltage and current signals are analyzed in time and frequency domains to characterize the metal transfer modes. Fig. 23 (A) depicts a typical variation in the arc shape with current-voltage and sensor signals (sound peaks). Statistical parameters like root mean square (RMS) and kurtosis can be processed and correlated with metal transfer behaviour. Arc sound signal kurtosis variation helps to identify weld defect like blowholes. The region in the weld bead where defects are present can be identified through the arc sound kurtosis variation, as shown in Fig. 23 (B). Features of acoustical signals have also been investigated in the laser welding process. Acoustic emissions from vapor plume or workpiece have also been used for defect detection laser welding [17]. However, the use of acoustic sensors in welding has been limited due to various issues ranging from difficulty in installation in industrial sites for contacting sensors and interference of work noise in case of non-contacting sensors. Although acoustic monitoring might be useful for assessing welding results, the delay in sound as a result of the distance between the sound generation and detection site makes acoustical sensing non-ideal for feedback or adaptive control.

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(A)

(B)

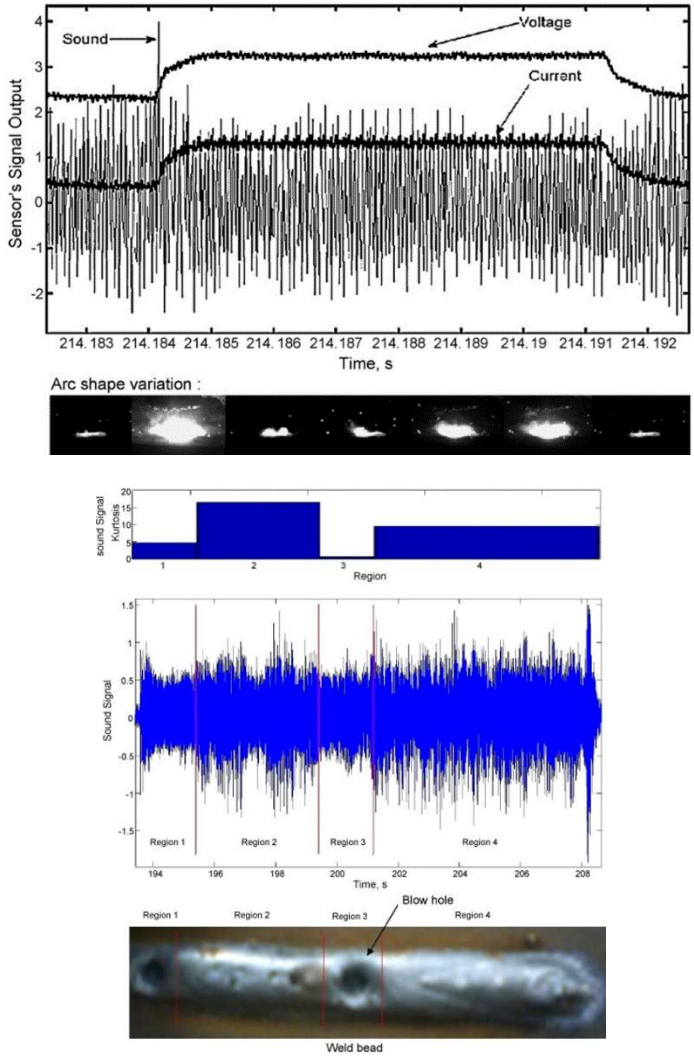

Fig. 23 (A) Change of arc behavior (shape) with current and voltage and the corresponding sound peaks, and (B) defect monitoring using sound kurtosis [26]

3.5 Displacement and Velocity Measurement

Vibrations imparted to the molten metal play a critical role in dendrite crystallization and fragmentation, affecting the weld metal's grain refinement [27]. The flow of the molten metal is affected due to the vibrations, which helps eliminate defects. Thus, it is critical to monitor the vibrations imparted in the vibration-assisted welding process and ultrasonic welding. Tarasov et al. [28] employed laser Doppler vibrometry during laser welding of stainless steel to investigate the effect of ultrasonic energy input on the weld characteristics and microstructure. The LDV allows obtaining the vibration velocity patterns directly for the workpiece that is welded. Another technique that provides displacement and velocity data for objects in motion is PDV. Lu et al. [29] incorporated the PDV technique for monitoring the USW of aluminium alloys. The velocity profiles obtained from PDV help discern the relative motion between the sonotrode, the sheets used for joining, and the anvil in USW. The PDV results correlate with mechanical testing results and weld microstructure, which helps to understand and quantify the bond formation. PDV is particularly useful when the velocities and corresponding displacements are to be captured for high-speed moving objects. One such particular application of PDV in the area of welding has been in impact welding processes like MPW [8], vaporizing foil actuator welding (VFAW) [30], where sheets are made to impact at velocities ranging from 300 to 1000 m/s to form the weld. The velocity and the angle (can be calculated from velocity data) with which the sheets impact/collide is crucial in such processes and directly correlate with the properties and the structure of the obtained joint. In a recent study [30], PDV has been employed to obtain the incident velocities at impact and thereby map the process-structure-property relation in impact spot welding (using VFAW), as shown in Fig. 24.

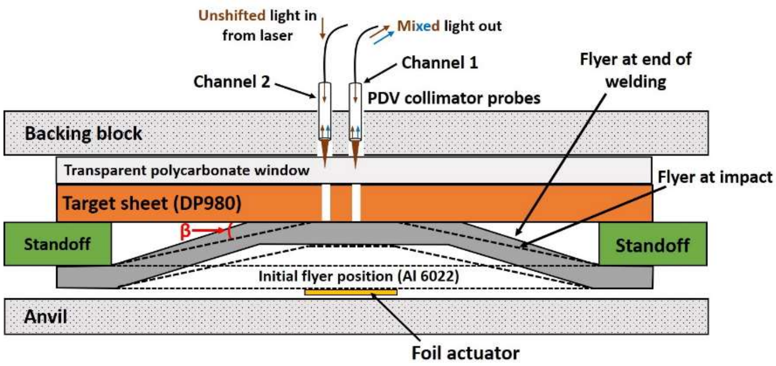

Fig. 24 Schematic of the experimental set up employed for velocity measurement using PDV in impact welding [30]

3.6 Force Measurement Measurement

Measurement of axial forces acting on the FSW welding tool is crucial as it is a crucial parameter that controls the metal flow [31, 32]. Experimental measurement of tool forces measured by the use of rotating component dynamometer for various welding parameters enables prediction of regions where the tool's failure is likely to occur and enables efficient tool pin designing. However, Su et al. [33] developed an alternative economical method to using a dynamometer or load cell that enabled simultaneous measurement of the forces (traverse and axial) and torque, acting on the FSW tool.

3.7 Electro-Magnetic Field (EMF) Measurement

Due to the arc welding processes' inherent nature, a magnetic field always surrounds the welding arc, which is possible to be measured and numerically simulated [34]. Any current-carrying element present in the vicinity of the field is acted upon by an electromagnetic force (EMF). The EMF plays a vital role in determining the weld pool flow pattern, which affects the welded joints' properties (both mechanical and metallurgical). The EMF also has other roles in various welding processes, e.g., grain refinement in gas tungsten arc welding, control of welding hot cracks, modification of element distribution, etc. Assessing the EMF is also critical due to the possible health hazards associated with it. Health concerns gaining much importance in recent years due to the rapid development of welding technologies. One of the most common ways of estimating the forces is through the use of gauss meters. Yoshida and Sawa [35] measured the Lorentz forces generated due to the magnetic flux to understand the effect of the forces on the arc blowout phenomena.

4. Future Directions

With rapid advancements in technology, there is an increased need for meeting requirements for welding through the development of new processes, materials and products. The gap between 'welding-an-art' and 'welding-a-science' needs to be narrowed, which necessitates a multi-sensor enabled welding system to extract, analyze and integrate all types of signals during and after welding, as shown in Fig. 25. The signals need to be analyzed deterministically as well as stochastically. Digitization of the welding process outcomes must be done to make welding processes Industry 4.0 ready. In the case of welding, where several welding sources (for different welding techniques) work simultaneously, it is advisable to have centralized control of all the machines to achieve the broader goal of zero-defect production for sustainable manufacturing. Automation of the maintenance of welding equipment and torches (change of tip, wire spool, gas cylinders, etc.) and autonomous defect detection and correction should be the focus of the researchers and manufacturers likewise. Another area that has been in focus recently is adaptive

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control of the welding processes, i.e. change in process parameters in response to the changing conditions.

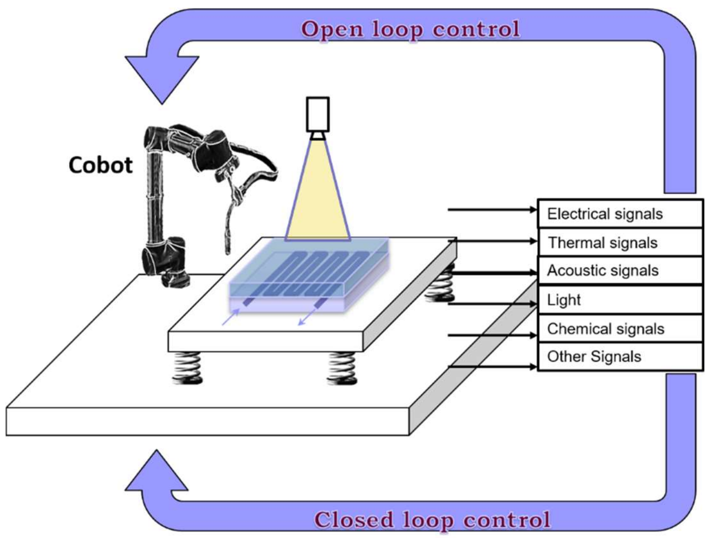

Fig. 25 An integrated monitoring and control for welding applications

The adaptive control is going to be much beneficial for AM processes that utilize welding to deposit the layers. During such processes, the adaption of the process based on the change in parameters with each deposited layer is essential for maintaining the build quality and properties. Due to the increased complexity of materials and part designs, it is essential to hybridize welding processes and welding with other manufacturing processes (e.g., welding and forming, welding and casting) wherein monitoring and control would play an important role. For additive or layered manufacturing, there lies a wide range of opportunities for both process and product development through a close-loop control. Thermal management for uniformity of properties, control of residual stress, adaptive process planning subject to each deposited layer, digital processing of electrical, thermal and acoustic responses, aggregate process response, and development of closed-loop controls (as seen in Fig. 25) are some of the future research directions for multi-sensor enabled layered manufacturing.

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