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Analysis of welding hazards from an occupational safety perspective

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Abstract:

Hazards generated during welding work are risky to human health. Knowledge of occupational health and safety (OHS) while working with different welding processes is essential. Through theoretical and empirical methods, the effects of welding hazards faced by welders in industries and the safety precautions for different welding processes are explained in this article. The welding goggle with filter shade number 10 is recommended for eye protection, particularly in industry settings for heavy-duty welding work. Most research has proven that welding hazards can lead to diseases such as musculoskeletal disorders (MSD), cancer, auditory nerve failure, pulmonary oedema, lung damage, pulmonary disorders, dermatitis, renal dysfunction, and pneumoconiosis. Among the steps of the hazard control hierarchy, the "elimination" step offers an effective alternative to prevent major accidents. Controlling fumes is crucial and is discussed through ventilation and other fume extraction methods. Forced circulation ventilation (FCV) provides better performance in fume control than natural circulation ventilation (NCV) if the height from the welding room roof is less than 5 m. Air velocity should be maintained at or below 1 m/s. Adhering to international standards like OSHA, ISO, HSE Act, and ASME is beneficial to avoid or reduce hazards.

Keywords: **chemical, hazards, health, occupational, safety, welding.**

Classification number: **2.3**

1. Introduction

Welding is a mechanical process of joining the faying surfaces of similar or dissimilar metals using heat or pressure where temporary fastening is not advisable. Metal joining is required in various sectors such as defence, nuclear power plants, aerospace, and automobiles. Welding work can be detrimental and poses risks if the right precautionary steps and safety measures are not followed by the welders [1]. Welding hazards can affect welders, compromising their physical conditions and health. The acute effects of the welding process include death, physical injuries, or mental distress [2].

New environmental and health policies focus on reducing industrial pollution and improving the safety conditions of workers. Ignorance of safety precautions can be hazardous for both the welding machines and the welders. It is crucial to follow the OSHA's guidelines since the welding process inherently has hazards during joining, cutting, gouging, chipping, and finishing. For welding in a hazardous area, a "hot work permit" is necessary, and a material safety data sheet (MSDS) should be consulted before starting.

The primary threats from welding that harm welders include heat, electricity, smoke, fumes, fire and gases [3], dust, and UV & IR rays. If the welding operations are not optimally executed, the resulting issues can range from musculoskeletal injuries due to repetitive stresses, nose, eye, and throat irritations, burns, auditory damage [4], suffocation, exposure to contaminants, and physical discomforts like sprains. Welding fumes can affect nearby individuals and negatively impact an industry's productivity if safety measures are not adequate. Prioritising the safety and health of workers is essential for a successful business. If the arc welding process utilises a flux with higher current and larger electrodes, it produces more fumes and smoke than other welding methods [5]. Welding fumes originate from sources like consumable electrodes, shielding gases, paint on base metal, molten puddles, etc. Fusion welding processes, such as arc welding, pose more risks than the solid-state welding techniques where joining occurs below the melting temperature of base metals without significant heat. However, arc welding can generate temperatures of around 5000^{o}C [6].

When addressing safety measures concerning welding, using safety data sheets is vital, helping identify health hazards, exposure limits, and preventative measures. Generally, welders should be well-trained in handling welding equipment, understanding Personal Protective

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Equipment (PPE), recognising welding hazards, and ways to mitigate them. Techniques like shielded metal arc welding, oxyacetylene welding, and gas metal arc welding are widely used and produce harmful visible, infrared & ultraviolet radiation. A notable hazard in welding is oxygen displacement in confined spaces. "Safety in welding" covers protection from electric shock, burns, UV and IR rays, chemicals, and airborne debris [7]. Other concerns include electromagnetic radiation, X-ray radiation [8], and intense heat present in high-energy welding methods like plasma, laser, and electron beam welding.

Though the literature on welding safety is limited, this article addresses that gap. A distinctive feature of this article is its comprehensive coverage of safety issues and precautions necessary for welding in industries. It aims to elucidate the various types of welding hazards, their causes, impacts on human health, and further discusses on hazard control and safety measures in different welding processes for the benefit of welders and surrounding workers.

2. Methods

This article is based on theoretical and empirical studies. The observation data was gathered by the authors during visits to welding industries, and the outcomes of discussions on welding safety with experts were used to prepare this manuscript.

3. Results and discussion

3.1. Welding hazards and their effects on health

In the welding industry, accidents are typically categorised into four: 1. Near miss incidents, 2. trivial, 3. minor, and 4. serious/major accidents. A near miss incident (a close call) describes a situation nearly leading to injury, such as a welder escaping hazards. 'Trivial' pertains to minimal damage like electrode damage or machine fault. 'Minor' accidents entail both injury and property damage, like electrocution or touching hot surfaces. Serious accidents lead to significant property damage and severe injuries, causing health complications, eye damage, and losses. These incidents can impact the owner, workers, and even have environmental implications.

In gas welding, damage to a gas cylinder's valve can trigger accidents due to its inherent force. Common causes of accidents in welding include: 1. Hot metals and fire, 2. Fingers caught during resistance and friction welding, 3. Debris entering eyes after welding, 4. Tipping gas cylinders, and 5. Electric shocks from welding equipment. These accidents and their health implications, as detailed in Table 1, originate from three main factors: environmental, human, and mechanical. The human aspect is particularly significant in steering industrial accidents. The leading cause of these accidents is neglecting safety rules. Additionally, poor communication and unfamiliarity with the welding machines and processes are also culprits.

Table 1. Risk factors in welding and health effects observed.

Factor	Causes of accidents/Risk/Hazard	Health effects and control measures
Environmental conditions	Inadequate lighting in the work area, rainy season, or presence of dust Electrocution, improper ventilation, poor housekeeping, discomfort due to room Temperature, heat, and radiation	Possibility for serious accidents and fatalities, lung damage, overstrain, suffocation, arc eye Can be controlled by good housekeeping and limits on welding time
Human	Working with welding machines without proper PPEs, lack of knowledge on the usage of welding machines and their parameters, fatigue due to overtime work Psychological factors of welders regarding working with hot surfaces, smoke-filled environment, fear of electrocution, poor housekeeping, poor ergonomics	Fatality due to improper usage of welding machines, minor and serious injuries, neck pain, burns, eye and nose irritation, overstress, and dehydration Health and mental fitness, use of PPEs, knowledge of proper machine usage to control accidents
Mechanical	Poorly maintained welding equipment, overspeed of solid-state welding machines Material breakage, overheating, unfamiliarity with machines and operation	Fatality, serious and minor injuries, electrical shock. Burns due to hot surfaces of machines and materials Proper machine maintenance, welding machines with safety guards can control risks

Welding hazards can be physical or chemical, both affecting welder health. Chemical agents include gases, fumes, filler materials, the chemical compositions of metals, and fire-related hazards. Respiratory dangers are divided into particles and vapours, with elements like iron oxide, lead, and zinc representing the former, and gases like argon and carbon monoxide representing the latter. Physical risks encompass noise, radiation, and electrocution. Harmful fumes from welding have been linked to cancer [9], and most welding operations produce noise above 90 dBA [10]. A study by O. Aminian, et al. (2021) [11] found that approximately 38% of workers are exposed to noise levels above 85 dBA, which, over time, can be damaging.

Welding emits fumes, forming solid particles around 1 µm in size, as a result of oxidation and condensation. These can settle in the lungs and lead to health issues. Some research suggests a relationship between fume production and welding process parameters in arc welding, noting increased emissions at higher parameters.

Hazards may arise from the chemical compositions of materials being welded, the specific welding processes, consumables used, and exposure length. Welding of galvanized iron, for instance, poses a lung hazard due to long-term exposure to iron fumes. Ergonomic considerations also play a role. Additional risk factors include lack of awareness, cigarette smoking, and welder psychology. Even minor burns in welding are significant, but if such injuries don't lead to lost work time, they may not be reported. Hazards specific to different welding methods are outlined in Table 2.

Table 2. Hazards of welding processes.

Hazards	Welding processes					
	PAW/Arc welding	*Oxy.-fuel*	*SMAW/TIG/MIG*	*SAW*	*FW*	*FCAW*
Noise	y	n	n	n	y	n
Heat, fire & burns	y	y	y	y	n	y
UV radiation	y	n	y	#	n	y
Electric shock	y	n	y	y	y	y
Ergonomics	y	y	y	y	y	y
Toxic fumes and gases	y	y	y	#	n	y
Bright light	y	y	y	#	n	y
Explosive gases	n	y	n	n	n	n

Note: y - hazard present, n - no hazard, # - hazard present if SAW flux is absent, PAW - plasma arc welding, SMAW - shielded metal arc welding, TIG - tungsten inert gas welding, MIG - metal inert gas welding, SAW - submerged arc welding, FW - friction welding, FCAW - flux-cored arc welding.

Heat stress is a primary hazard in the industry, influenced by proximity to heat, room temperature, and clothing. Other health issues for welders include: 1. Vibration from welding tasks, 2. Physical strain due to prolonged postures, 3. Unsafe handling of equipment, and 4. UV and IR radiation exposure. Burns, a consequence of intense welding heat, can be detrimental. Proper protective clothing, such as leather attire, can mitigate these risks. Radiation impacts welders' eyes and skin but can be managed using appropriate protective equipment.

Electricity can pose hazards such as electrocution and electrical shock. Damaged electrical appliances or equipment, such as electrodes or frayed wires, may be primary culprits. Fumes, produced during the arc welding of metals by an electrode and the introduction of filler metals, can lead to cancer and respiratory disorders. Fumes from cadmium (Cd) and manganese (Mn) are particularly hazardous. These risks can be reduced with appropriate respiratory and ventilation systems. Managing mechanical hazards is demanding. This includes situations like handling sheets or metals intended for welding and managing welding equipment. Sheet metals might have sharp edges that could injure the welder's hand, and metal rods or plates could pose ergonomic risks to welding staff due to their weight. Such hazards are typically mitigated through proper training in material handling and the appropriate use of PPEs, such as masks, gloves, and safety shoes. It is widely recognised that MSDs can be triggered by the use of vibrating tools, such as chipping and grinding tools, and pneumatic equipment in welding. Fig. 1 depicts the hazard curve established by the relationship between exposure time and the sound level that might harm the hearing of personnel [12]. If a welder is exposed to a sound level of 110 dBA for 15 minutes, it could affect his auditory nerves. Similarly, exposure to a 90 dBA sound for 8 hours (480 minutes) could lead to auditory disorders.

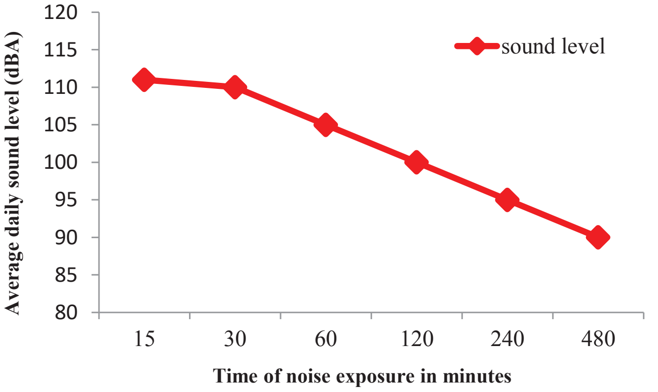

Fig. 1. Relationship between sound level and exposure time.

The literature identifies 5 hazards involved in nearly all welding processes, as illustrated in Fig. 2. The nature of welding tasks is influenced by ergonomic factors. Welding methods that neglect ergonomic considerations can lead to musculoskeletal injuries (MSIs) and MSD. Such injuries often result from strains and back pain experienced by welders working in static postures. The weight of the PPE a welder wears can also contribute to neck and hand discomfort. Repetitive motions during welding heighten the risk of injuries. It is crucial to assess ergonomic factors in the industry to manage and mitigate health risks. Table 3 itemises various chemical agents produced during fusion welding processes. Key gaseous hazards in welding environments include NO_X, O_3, CO_2 and CO [13]. These harmful gases can lead to symptoms such as nausea, headaches, dizziness, throat irritation, shivering, sweating, and dryness - often referred to as metal fume fever. Physical agents can also impact welder health, as detailed in Table 4. For instance, prolonged exposure to heat, a physical agent, can result in heat-related ailments like heat cramps, heat rash, heat exhaustion, heat oedema, and heat syncope [14]. Noise, considered non-beneficial in the welding setting, also poses a health risk due to its detrimental effects.

Fig. 2. Five major hazards in welding processes.

Table 3. Health effects identified due to chemical agents in the welding process.

Agents	Type	Source	Health effects
Cadmium oxide	Fumes	Cadmium-related materials, electroplating	Respiratory problems, muscle aches, carcinogenic effects, headache, pulmonary oedema, fever, lung damage, death
CO	Gas	CO_2 welding, coating	Nausea, dizziness, headache, cardiovascular symptoms
Phosphine, Phosgene	Vapour	Metal-coating, incomplete combustion	Eye irritation, kidney damage
ZnO_2	Fumes	Painted and galvanized metals	Metal fume fever, zinc poisoning, death
O_3	Gas	Welding arc	Lung issues, pulmonary disorders
Nitrogen oxide	Gas	Welding arc	Chronic bronchitis, emphysema, pulmonary fibrosis, pneumonitis
Ni	Fumes	Nickel-containing metals	Lung cancer, respiratory tract irritation, dermatitis, renal dysfunction
Mn	Fumes	Welding, high tensile steel	Metal fume fever, kidney damage, insomnia, nervous system disorders
Magnesium oxides	Fumes	Magnesium alloys, base metals	Eyes and nose irritation, cough, fever, chest pain, fire or burn
Iron oxide	Fumes	All ferrous metals, base metals	Siderosis, lung irritation, nose irritation, pneumoconiosis
Compressed gases	Gas	Gas welding	Asphyxiation and respiratory problems, fainting
Beryllium	Fumes	Beryllium alloys	Lung inflammation
Lead	Fumes	Lead alloys, coatings, paints	Damage to the liver, heart, and kidney

Table 4. Health hazards and control measures owing to physical agents in welding process.

Agent	Causes	Symptoms/hazards	Control measures
Hot surfaces and the environment	Air movement and humidity in the welding area, hot surfaces of welds	Excessive sweating, weakness, burns, fainting, confusion, body heat, reduced urine output, etc.	Proper ventilation, and proper PPE needed for insulation from heat
Noise	Gouging, arc cutting and welding	Hearing loss, auditory nerve failure, poor sleep quality, psychological torture, echo	Sound barriers around the welding area, noise absorbers, earplugs/ear-muffs, helmet usage
Radiation	Welding light (UV, IR, visible light), skin contact	Eye irritation, skin inflammation, melancholy, mental stress, headache, itchy skin, ultraviolet keratitis, eye pain caused by exposure to ultraviolet rays	Goggles, shield/ helmet, band-pass filter

Workplace exposure limits (WELs) are established to mitigate the overexposure of welders to welding hazards. Eight-hour and fifteen-minute time periods represent the exposure limits for the long-term exposure limit (LTEL) and short-term exposure limit (STEL), respectively. The exposure limits for 8 hours of various hazardous substances released during the welding process, based on the UK system, are illustrated in Fig. 3. It is advised to keep exposure below WEL. For example, the WEL values for iron oxide fume hazard stand at 5 mg/m³ for LTEL and 10 mg/m³ for STEL. These values vary depending on the specific hazard. The limit for nickel and manganese should ideally not exceed 0.5 mg/m³, and it is emphatically suggested that the limits for cobalt and cadmium be 0.1 mg/m³.

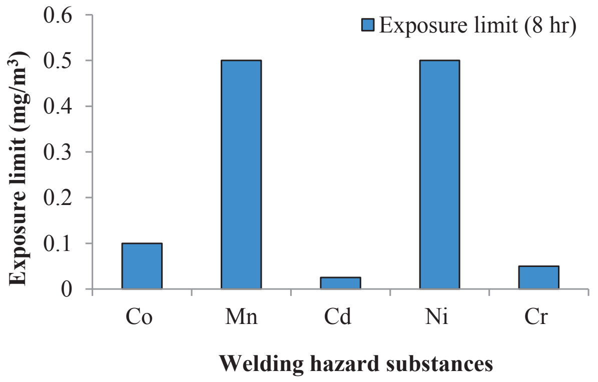

Fig. 3. Exposure limits of hazardous welding substances for 8 hours.

Gas cylinders are utilised as they are the source of heat production for welding operations. LPG, hydrogen, acetylene, propane, and butane gases are typically employed in welding. These cylinders can pose hazards, as their gas pressure increases when exposed to elevated temperatures. The risks associated with these gases include explosion, fire, propulsion of the cylinder, and more. They are characterised by their toxicity, flammability, and difficulty in manual handling.

Oxygen, being odourless, can easily ignite and explode. Acetylene, with a maximum flame temperature of 1755°C with air and 3200°C with oxygen, is used as fuel gas in gas welding for joining metals and emits a garlic-like odour. Misunderstandings related to gas cylinders can lead to accidents; this can be mitigated by recognising that acetylene (maroon-coloured cylinder) has left-hand threads, while oxygen (black-coloured cylinder) has right-hand threads. It is crucial first to close the acetylene valve and then the oxygen to prevent backfires in the event of an accident. Acetylene, being lighter than air, accumulates in roof spaces. The gas is stored in a cylinder at 15 bar pressure and a temperature of 15°C. It is explosive and highly reactive. Conditions are such that the time interval from initiation to explosion could span several hours.

Explosions can be triggered by overheating, dropping, and mechanical shocks as they induce decomposition within the acetylene gas cylinder. When reacting with silver and copper-containing materials, it forms explosive compounds called acetylides. The recommended safety precautions include wearing an oxy-acetylene safe outfit, ensuring cylinder hoses are not entangled, refraining from using acetylene gas at pressures above 100 kPa, keeping a fire extinguisher on hand during welding, and opening the acetylene gas cylinder valve only one and a half turns while keeping a wrench on it. It is advised to avoid piecing hoses together and having any damage on the hoses connecting the cylinder and welding torch in gas welding.

Storing gas cylinders separately in a yard is essential. Ideally, a firewall of a minimum of 2 m should separate different categories of gas cylinders. If a firewall is impractical, the distance between LPG cylinders and other gas cylinders should be at least 3 m. The acetylene cylinder, when in an upright position, should be double-chained at 1/3 and 2/3 of its height for safety. Such measures help avoid potential explosions. For instance, if a cylinder's height is 1.25 m in an upright position, one chain should be positioned at 0.83 m and another at 0.4 m from its base. Every 1/3 m of its total height, the cylinder must be chained for optimal safety.

Cylinders should not come into contact with heating sources or electrical systems and should be stored in well-ventilated areas. In the work environment, gas cylinders must be positioned at least 6 m away from combustible/flammable paints. Oxygen and acetylene cylinders should ideally be stored separately. If any partition exists between acetylene and oxygen storage areas, this barrier should be 0.45 m taller than the tallest cylinder and extend 0.45 m from the outermost cylinder. It is crucial not to use oxygen near any flammable materials due to its combustion-enhancing properties. When transporting the acetylene cylinder, ensure it is either in a vertical position or tilted no more than 60^o, using a trolley.

Rolling cylinders from one location to another is not advised. When utilising inert argon gas in a confined space, it tends to settle at the bottom of the welding area since it is denser than air, successively reducing the oxygen content. When ceasing the gas welding process for an extended period, it is necessary to close the cylinder valves and then discharge the gas pressures from regulators and hoses through the welding torch. However, gases can still pollute the welding area. For instance, helium fills spaces from top to bottom as it is lighter than air.

During arc welding, there is a potential risk of electric shock or electrocution. Human skin, when wet, exhibits reduced resistance to current compared to dry skin [15]. An electric shock from sources such as 240 volts (domestic appliances) or 415 volts (industrial machinery) can result in fatal accidents or severe injuries, often causing the victim to be thrown a considerable distance due to convulsion. Electric shocks can also arise from welding apparatuses [16]. A current of 50 milliamperes (mA) can be lethal; at this magnitude, respiration becomes difficult and can cease. The voltage in the electrode holder can surge to 80 V quickly when an arc is not established. In such scenarios, if an operator contacts a conductive part of the electrode holder, they may experience an electric shock leading to significant injury. Devices known as automatic electric shock prevention devices can mitigate this hazard as they promptly reduce the voltage. Moreover, proper grounding and insulation can further minimise risks. Electric shocks can sometimes be felt due to the deterioration of a flexible cable or electrode holder. Other times, shocks result from improper wiring of an arc welding machine. Factors such as wet clothing or welding environments during rainy seasons, poorly insulated connections, ungrounded plugs, and worn-out cables typically induce electric shocks. Table 5 discloses the electrical hazards related to high and low voltage in arc welding and their ramifications on humans.

Table 5. Arc welding electric shock hazard and health issues at high and low voltage.

Fault/hazard	Health issue
Lack of welding machine earthing	Shock, severe burns, fatal
Poor insulation and damaged cable	Fire, property damage, shock, fatal,
Oversize fuse	Shock, burn
Inadequate connection	Fire, overheating

3.2. Safety issues and measures in different welding processes

Fumes, electric shock, heat, brightness, radiation, ergonomics, and noise constitute the primary hazards in the majority of welding processes. Welding is intrinsically a high-temperature operation. Welding safety encompasses the comprehensive protection of workers from hazards such as fumes, hot metal, splatters, heat, and radiation. Therefore, it is imperative to secure a "hot work permit" when operating under these conditions. Beyond complying with Environment, Health, and Safety (EHS) standards, this permit is a legal requisite according to both Indian and international statutes. The enactment of ISO standards necessitates this. The engineer or supervisor overseeing the welding or other high-temperature works applies for this permit. The plant manager, in collaboration with the safety professional, evaluates the work site and approves the hot work, provided all criteria on the permit checklist are met. This encompasses considerations such as PPE, protocols for hot work, welder training, and more.

A suitable working environment is pivotal in mitigating hazards during welding and reducing exposure to health-damaging substances. Welders must have ample space to manoeuvre and operate effectively. Appropriate ventilation and roof height are compulsory in welding areas to dissipate fumes and smoke, ensuring workers remain undisturbed. In terms of safety, it's crucial to have fire extinguishers, hydrant systems, fire monitoring systems, and machine guarding systems proximate to welding machines to shield operators from potential harm. Welders should receive specialised training on the correct use of PPEs and adherence to safety protocols. Welding machines should be halted when substituting materials and subjected to a preliminary inspection before initiating the welding process. Welders must also be mindful of psychological factors, such as stress, complacency, and job interest, to preclude human errors.

Anticipated hazards for gas welding include hot surfaces, fumes, toxic gases, and potential cylinder explosions. In contrast, arc welding may introduce risks of electrocution, spatters, hot surfaces, fumes, smoke, and toxic gas emissions when welding materials that contain harmful substances [17]. In heavy industrial settings, adherence to the safety checklist is paramount to prevent mishaps during welding activities. The electrical supply to the welding machine needs rigorous examination to ensure its hazard-free. Any paint, coatings, or plating on the base metal must be removed prior to welding to prevent metal fume generation. Welding tasks should only be undertaken by competent individuals under stringent supervision. From an electrical safety perspective, the open-circuit voltage of the power unit must not be excessive, limited to a maximum of 80 V AC, or 48 V AC in damp areas [18].

Gas cylinder valves, hoses, their positioning, and the isolation of cylinders are essential to circumvent heat source interaction before and post gas welding. Welding zones should maintain good ventilation and be devoid of flammable materials. The functionality of all welding machines and related equipment should undergo regular assessment. The state of PPEs, firefighting tools, and welding machine insulation against both natural and artificial hazards must be routinely inspected. The "job card" for welding tasks requires meticulous scrutiny by the sanctioned authority, ensuring the qualification of welders, the equipment in use, requisite PPEs, their accessibility, welding duration, and the designated work space. Conclusively, it is imperative to confirm the deactivation of welding machines post-operation. Generally, the employment of gas cylinders in gas welding is indispensable. However, mishandling or improper storage can precipitate accidents. Table 6 enumerates the precautions to be heeded during arc and gas welding.

The safe storage and handling of gas cylinders is imperative. Herein, we propose several recommendations for cylinder safety to mitigate hazards. Cylinders should be stored in a well-ventilated area, and the use of uninsulated cylinder hoses across trafficked areas should be avoided. A mixture of water and soap or detergent is preferable for detecting leakage, as opposed to using a flame [19]. When stored, the valves of the cylinders should be oriented uppermost. Secure cylinders with a chain to prevent unnecessary movement during storage, and ensure cylinder valves are closed after use. It is prudent to avoid storing cylinders near sources of heat or electricity. During welding operations, welders should manage any flashback into the hoses. The use of oil, water, and grease on cylinder appliances should be avoided, and trolleys are recommended for cylinder transport between workplaces. Prevent cylinder rust and the introduction of dust, grit, and sand into the hose or valve. If gas welding is utilised within a boiler, cylinders should be stored externally due to the confined nature of the working space. While forced fans can be utilised for ventilation during welding [20], the use of oxygen is not recommended as it exacerbates potential fire hazards. Flashback arrestors can halt the backflow of gas when the flame begins burning within the hose. Welding on painted surfaces poses risks of nausea and inhalation of chemical contaminants, necessitating appropriate PP). During gas welding, maintaining a gas torch welding gap of 5-10 mm and a standoff distance of a minimum of 160 mm is advised.

Table 6. Safety measures in arc and gas welding.

Arc welding process	Gas welding process
Bright light, IR, and UV rays are produced by arc welding. Eye and face protection equipment is essential for all involved.	Special attention must be paid to welding materials, especially toxic ones.
Appropriate PPEs must be worn. Ensure welding machines are switched off when not in operation.	Hoses connected to gas cylinders must adhere to safety standards.
Earplugs can mitigate the disturbance caused by the arc sound.	Appropriate PPEs are essential during the joining process.
Ensure welding materials are clean and free from rust. Maintain a tidy work area.	Protect workers from skin contact with hot surfaces, fluxes, and similar hazards.
Guarantee proper insulation of the welding torch, cables, and machine.	Handle acetylene with care.
To avoid electrical shocks, stand on wooden or rubber mats while welding.	Before welding, clean weld surfaces with acetone and remove any coatings.
Avoid wearing wet clothes or gloves. Implement measures to prevent welders from inhaling harmful fumes.	Ensure gas cylinders are securely stored and handled safely during transportation.

Understanding welding protection utilities and their functions is essential. Fume extraction systems [12] remove fumes from the welding space, ensuring the welder's health is not compromised. Appropriate selection of breathing or extraction systems is crucial for a safe welding environment. Welding curtains or fireproof canvases protect personnel working in proximity to the welding area. As arc welding poses multiple injury risks, the proper use of PPE, including boots, fire retardants, goggles, masks, helmets, protective clothing, and leather aprons, is crucial. For fresh air supply, managing oxygen content and supplying fresh air to welders during operations is essential. Safety boots with steel toes protect from potential injuries and electric shocks due to their shock-resistant soles [21]. In respirators with blowers, embedded air purification systems introduce fresh air to the user.

During resistance welding, resistance spot welding, commonly used in automobile manufacturing, poses risks such as finger entrapment between electrodes and welding spatter. Additional hazards include electric shocks, hot metal exposure, and electromagnetic fields. Safety precautions, such as protective screens and the use of PPE, are recommended. Sensor-embedded equipment in resistance spot welding machines detects obstructions and halts operations, reducing accidents [22]. Minimising the gap between electrodes can prevent finger entry. For safety, resistance welding machines can be leg-operated to reduce hand injuries.

Guarding, particularly fixed or interlocking types, is a vital safety feature. Robotic spot welding requires safety interlock systems due to the rapid movement of robot arms. Hazards associated with spot welding, depicted in Fig. 4D, include MSDs in the neck, wrist, shoulder, and back. Technological advancements like the "Car-O-Liner CTR9", illustrated in Fig. 4E, reduce these ergonomic issues. In Figs. 4D and 4E, welders are shown performing spot welding tasks on automobile bodies. Thanks to innovations such as the Advanced Resistance Spot Welder, the incidence of MSDs in welders is reduced, as evident in Fig. 4E.

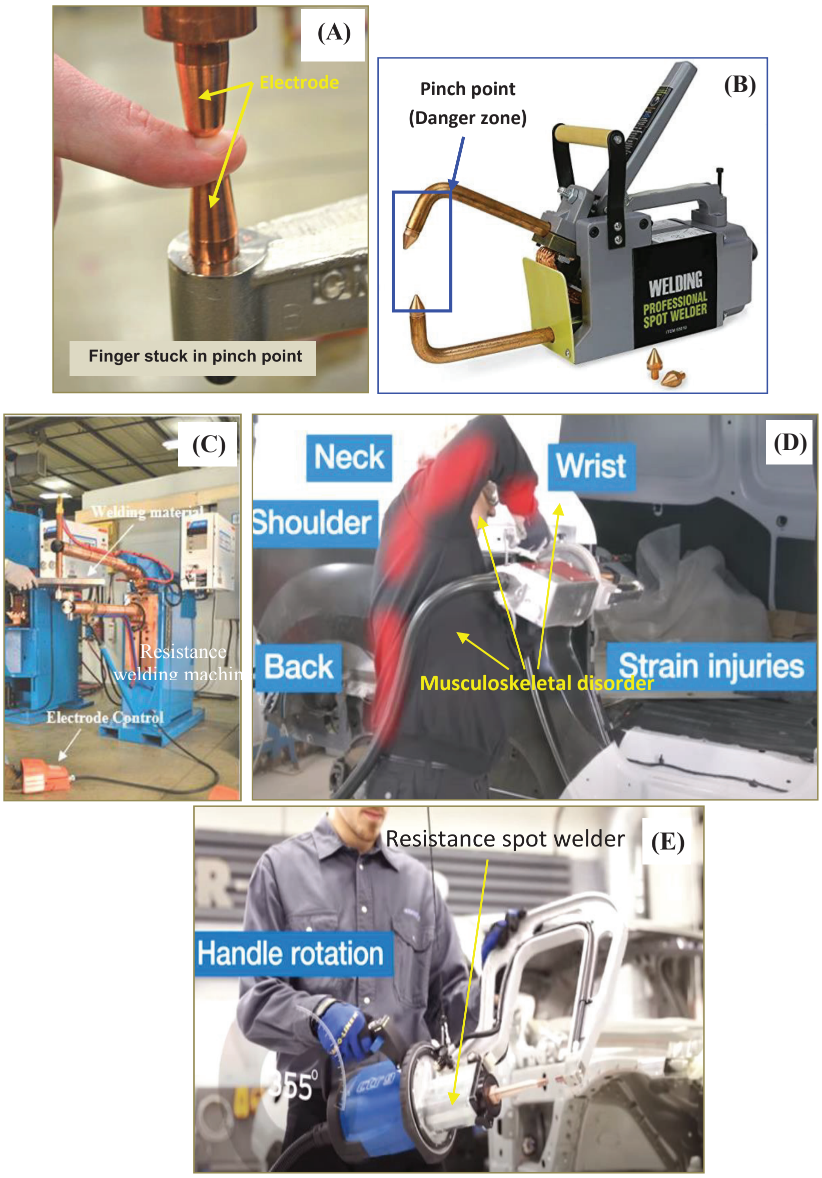

Fig. 4. (A) Finger caught between electrodes in resistance welding, (B) portable resistance spot welding machine with pinch point and danger zone, (C) welding of material with leg operation, (D) resistance welding hazards, and (E) advanced resistance spot welder (Car-O-Liner CTR9) with zero hazards.

While considering safety in laser and explosive welding, laser welding (LW) should be conducted within an enclosure in line with safety guidelines. It has been determined that the primary hazards associated with LW include fumes, glare, radiation, and direct exposure to the laser beam. The laser beam may harm the operator's skin and eyes. To mitigate beam-related hazards, it is prudent to minimise direct interaction between the operator and LW. Implementing enclosures around the machine's working area, safety curtains, and interlocking guards is strongly advised. However, LW presents a unique hazard distinct from other welding techniques: the risk associated with high laser voltage. Therefore, technicians handling LW machine maintenance should be well-versed in procedures and thoroughly familiar with the equipment. Existing literature notes that CO_2 does not transmit through glass materials. Consequently, doors of CO_2 laser-embedded welding machines should be constructed of such materials to shield operators from beam-related hazards. Both operators and repair personnel should undergo training about the operations, safety hazards, and preventive measures associated with the LW machine.

Explosive welding is a solid-state welding method that does not melt the material; joining occurs due to the high-impact energy provided by chemical explosives. Here, metals like sheets and plates are bonded using energy from chemical explosives. Careful attention must be given to factors such as the distance of the process, the specific chemical utilised, its handling, the target plate angle, applied pressure, and detonation speed.

The hazards inherent in the rotary friction welding (RFW) process include noise [23] from the motor and chuck rotation, pinch points, elevated forging and friction pressures, and the movement of the hydraulic actuator during welding. There is also the risk of an operator's hand getting trapped between the axially moving system and the chuck in RFW [24]. The welding region, or "danger zone" in friction welding, is a high-risk area where weld specimens are placed. Although FW is considered environmentally friendly [25], it is advisable to employ machine guards and noise-controlling enclosures around the FW machine to mitigate noise levels [26]. When operating the FW machine, safety protocols must be adhered to. Operators should avoid loose clothing, unrestrained hair, wrist bracelets, and necklaces, as these items can pose risks. A transparent sliding door guard or a sliding grilled gate is recommended for the machine's front side to facilitate the inspection of weld specimens during loading and unloading. A fixed guard is preferable for the machine's rear [27]. Implementing interlocking mechanisms or automation is advised to shield welders from potential hazards. Additionally, a sensing system that detects human movement and promptly halts machine operation can be instrumental in preventing accidents.

3.3. Hazard control

The hierarchy of hazard control is presented in Fig. 5. It encompasses personal protection, as well as administrative and engineering controls. In this context, "PPE" is deemed the least effective for welding hazard control because its efficacy depends on various factors, such as the availability of PPE, individual users, the working environment, and the duration of welding, among others. PPE is utilised either singularly or in combination in accordance with OSHA standards [28]. However, the effectiveness of PPE in countering health hazards remains minimal. PPE includes earplugs, gloves, goggles, safety glasses, welding helmets, protective shields, aprons, respirators, and more. Welding fume hazards can be mitigated using PPE-respiratory devices. Auto-darkening filters (ADF) in welding helmets have been employed to minimise injuries such as arc-eye burns caused by UV rays during welding [29, 30]. Safety gloves safeguard the welders' hands, while asbestos or leather aprons shield their torso and thighs. Protection for the head during overhead welding is essential, and a leather skull cap, helmet, or peaked cap (kepi) proves valuable for this purpose. The welder's body can be further protected using leather jackets and leggings.

Training for welders falls under administrative controls. Three types of training can be provided: basic, technical, and specialised. The nature and depth of training are contingent on the welders' tasks and their experience level. "Administrative control" involves modifying work procedures by implementing new safety policies within the welding sector. On the other hand, "engineering controls" aim to separate individuals from hazards by enclosing the welding area, utilising methods such as guarding systems and adequate ventilation. Another method of control is "substitution", which entails replacing the hazard. If certain hazards are particularly severe, they might need to be entirely removed or "eliminated", a strategy which is highly effective within the control hierarchy.

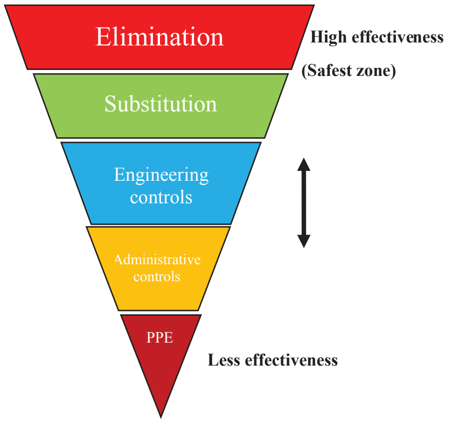

Fig. 5. Hierarchy of hazard control.

In welding, both major and minor accidents necessitate immediate first-aid intervention. Electric shocks, burns, and eye injuries are predominantly linked with welding hazards [31]. Keeping a first-aid kit in the vicinity is advantageous. To circumvent electric shock risks, one should disconnect the power source, avoid touching any surfaces with bare hands, and don appropriate non-conductive clothing and gloves. If an individual is injured, measures should be taken to ensure their airway remains open, and trained personnel should administer first-aid. In the event of burns, the affected area should be cooled with water for a minimum of 10 minutes and then dressed. Depending on the burn's severity - such as internal damage or deep burns categorised as 1st, 2nd, or 3rd-degree - further medical attention might be necessary. If foreign substances like dust or fumes contact the eyes, immediate flushing with a suitable solution is imperative. Following this, if any debris remains, a professional examination is recommended. Goggles should be worn during activities like gouging, etching, and chipping of weldments. For brief welding tasks, a face shield can be utilised, whereas extended welding sessions might necessitate a helmet with a hood. Prolonged exposure to UV rays mandates consultation with an eye specialist. When analysing welding fume samples, occupational chemical agent guidelines offer insights into sampling procedures and calculation methods. Additionally, guidelines on thermal stress in workplaces are invaluable for assessing hazards related to high-temperature conditions. It is prudent to adhere to approved regulatory requirements and welding manuals, which outline fundamental criteria for hazard assessment, welder qualifications, and control measures [32]. If risk levels escalate in the vicinity of the welding area, they should be reduced and maintained below stipulated thresholds. Given that injured workers require immediate first-aid, specially trained medical staff or ambulance personnel should be available around the clock within industrial settings to assist casualties.

3.4. Eye protection and fumes control

The welding process, particularly arc welding, produces intense light which can adversely affect the welders' eyes and potentially lead to blindness. Thus, provisions must be made for eye protection to shield against this light. The standard OSHA's 29 CFR 1910.252 section (b) (2) mandates eye protection during welding [33]. Wearing a welding helmet (ANSI Z49.1) equipped with the appropriate shade number for the filter ensures the protection of both face and eyes. The correct lens shade numbers [34] for different welding processes should be adhered to as delineated in Table 7. Welding with intense glare requires a higher shade number. For instance, oxy-fuel gas welding utilises lenses between shade numbers 4 to 8. The shade numbers for flux-cored arc welding, plasma arc welding, and gas metal arc welding range from 8 to 14. Similarly, for the safety of welders, the recommended lens shade numbers for gas tungsten arc welding and shielded metal arc welding are between 9 to 14 and 10 to 14, respectively.

Table 7. Recommended lens shade number for the welding process.

Metal welding processes	Range of lens shade number
Oxy-fuel gas welding	04-08
Gas metal arc welding	08-12
Flux-cored arc welding	08-14
Plasma arc welding	08-14
Shielded metal arc welding	10-14
Gas tungsten arc welding	09-14

The construction of ADF and its efficacy against UV light are pivotal. It comprises liquid crystal (LC) placed between each polarising filter to enhance its effectiveness. Likewise, a band-pass filter (BPF) is employed to shield against UV and IR rays, permitting only visible light to pass through. The arrangement within the face shield, designed for the welding helmet, includes a protective glass made of polycarbonate positioned closest to our eyes to defend against chipping particles. This is followed by the filter shade glass which screens out the IR and UV rays emitted by the arc welding light. Finally, another protective glass is installed to guard against spatter during welding. Fig. 6 depicts the appropriate shades in relation to the amperage used for welding operations to protect eyes from potential hazards. The choice of filter glasses is contingent on the current utilised for welding. For instance, for a current of 100 A, a shade number below 10 is suitable. As amperage increases, so does the required shade number, with numbers 12 and above recommended for currents exceeding 300 A. Typically, shade number 10 is adequate for most welding processes.

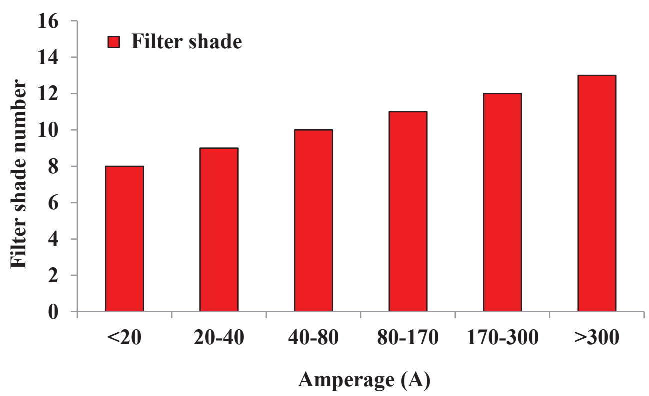

Fig. 6. Relationship between amperage in welding and filter shade number.

Adequate ventilation is imperative in the welding area to mitigate welding smoke and fumes. Welding fume exposure control is typically achieved using smoke extraction and ventilation systems. However, an overly congested area can compromise the efficiency of these systems. Two prevalent types of ventilation are utilised in industries: dilution ventilation and local exhaust ventilation. The former involves wall or roof exhaust fans and functions by diluting contaminants to levels below exposure limits (e.g., threshold limit values and permissible exposure limits) by introducing large volumes of air. However, this method can occasionally prove insufficient as it might allow contaminants to enter the welder's breathing space. Conversely, local exhaust ventilation, designed specifically to accompany welding machines, efficiently extracts gases and fumes produced during welding. It comprises a hood, duct, fan, and air cleaner, crafted to prevent fumes from entering the welder's breathing zone. The efficacy of the ventilation system is determined by the distance of the welding booth's hood from the welding source and the exhaust-air velocity (recommended at 0.5 m/s) [35]. Due to this reduced air velocity, fumes, gases, and smoke generated during the welding process remain away from the welder's breathing zone. Welding within confined spaces is inadvisable unless adequate ventilation is ensured.

Figures 7 and 8 illustrate ventilation and fume extraction techniques designed to minimise hazardous concentrations, and a welder's face shielded with PPE during welding. Fig. 7A showcases the extraction of fumes and particles through the ventilation duct. M.H. Lee, et al. (2007) [36] introduced a new model, as seen in Fig. 7B, tailored for fume control. The ventilation system atop a booth, depicted in Fig. 7C, is devised to regulate particle concentrations around the welder's face [36]. Fig. 7D [37] displays a movable ventilation duct, adept at capturing fumes wherever welding occurs and facilitating easy discharge without environmental impact [38]. In this fume control setup, the maintained air velocity is approximately one m/s. The Health and Safety Executive (HSE) strongly advocates the Control of Substances Hazardous to Health (COSHH) regulations, specifically concerning welding fumes, to uphold public health and safety. Typically, the HSE recommends the employment of local exhaust ventilation and respiratory protective equipment in environments with welding fumes. This is applicable to welding processes such as gas, TIG, MIG, arc, and resistance spots.

The welding fumes, linked to conditions such as asthma, cancer, and pneumonia, have not been entirely eliminated during fusion welding processes but can be safely managed with appropriate welding fume control techniques. Some of the fume extraction techniques endorsed by HSE to expel the fumes are depicted in Figs. 8A-8C [39]. In one technique (Fig. 8A), the fumes produced during welding are removed through slots or holes in the welding chamber. The fume-capturing hoods can be automated and mobile, while battery-powered PPE hoods can prevent welders from inhaling fumes (Fig. 8B). The fume extraction via slots or holes, positioned near the welding torch (Fig. 8C), ensures immediate removal of fumes before reaching the welders' respiratory zone. These methods effectively regulate the volume of fumes accumulated in the welding booth. By utilising these ventilation and fume extraction approaches, the build-up of fumes within the welding area can be controlled.

The extent of dust and fumes exposure to welders is contingent upon the welding technique, ventilation efficacy, practices, and locale [40, 41]. When ventilation is not viable, respiratory protection systems must be employed. Respiratory conditions are prevalent amongst welders [42], including respiratory tract cancer [43], especially for gas and arc welders. Thus, it is imperative to curtail exposure to welding fumes. According to NIOSH (National Institute for Occupational Safety & Health), an approved respirator is essential, and each welder should be adept at its efficient usage. Every respirator is characterised by an assigned protection factor (APF), indicating its protective capacity. The maximal permissible concentration of a substance during welding can be determined by multiplying the APF value of the respirator with the exposure threshold for that substance. Atmosphere-supplying respirators operate independently of ambient conditions, whereas air-purifying respirators cleanse the inhaled air, filtering out particulates. Welding respirators should incorporate particle filtration since fumes predominantly contain particles.

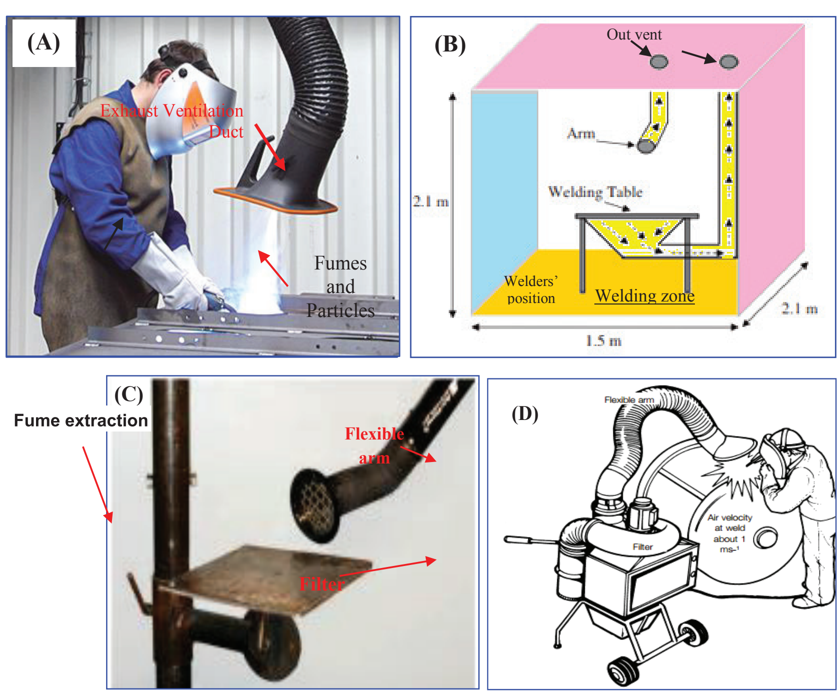

Fig. 7. Ventilation setup: (A) Modified welding room with duct; (B) Welding table with modified ventilation setup; (C) Exhaust pickup arrangement; and (D) Mobile fume control setup.

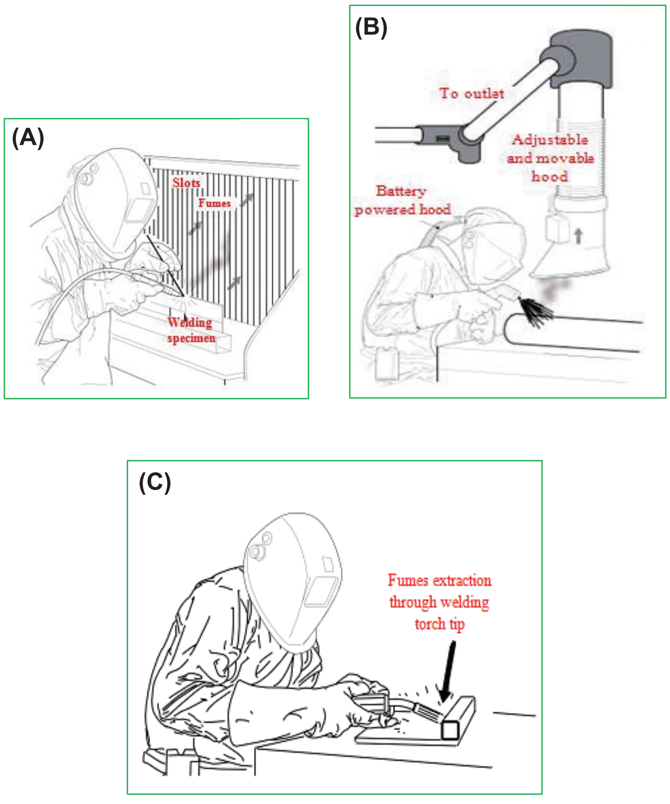

Fig. 8. Welding fume control [39].

4. Conclusions

Given the paucity of research articles in the realm of welding safety, this article elucidates the causes and effects of welding hazards across diverse processes on welders' health, alongside safety precautions and hazard control strategies. The principal contributors to welders' health deterioration encompass inhaling welding fumes, perilous practices during welding, flawed specimens and equipment, UV and IR emissions from welding lights, and heat radiation. A Hot Work Permit (HWP) is imperative for high-risk welding tasks, and risk assessments or safety audits should be systematically conducted within industries to safeguard both workers and assets. Welding hazards can lead to ailments such as nausea, headaches, respiratory conditions, and vertigo. Symptoms of metal fume fever include throat discomfort, chills, perspiration, and dryness. A 3-m distance should be maintained between oxygen, LPG, and acetylene cylinders, and gas containers should be situated at least 6 m away from hazardous zones. In many welding processes, filter shade numbers between 8-10 are utilised for ocular protection. As the working amperage escalates, a higher shade number for the welder's face shield is recommended. The design of fume extraction systems and ventilation efficiency is pivotal in determining fume control. For welding in confined spaces, a forced circulation fan is recommended for fume dispersal, whereas natural circulation is favoured in spaces with a 5.5 m ceiling height. Fume accumulation can be efficaciously managed through slots and holes in welding tables or at the torch's tip. In the hierarchy of hazard control, elimination and substitution remain paramount for ensuring a secure environment. An ambient light intensity of approximately 200 lux is advised for the welding workspace.

CRediT author statement

S. Senthil Murugan: Investigation, Methodology, Data collection, Writing - Original draft preparation; P. Sathiya: Revision, Conceptualisation, Supervision.

COMPETING INTERESTS

The authors declare that there is no conflict of interest regarding the publication of this article.

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