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# Oxy-hydrogen gas as a sustainable fuel for the welding industry: Alternative for oxy-acetylene gas

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ABSTRACT

The urgent need to address climate change has prompted researchers to explore sustainable power generation methods using low or net-zero fuels and energy storage. Historically, gases derived from acetylene or LPG have been used for welding in factories. Despite its negative effects on the environment and human health, acetylene gas remains widely used. Examples of pollutants released from acetylene gas include carbon dioxide and carbon monoxide, both of which contribute to the greenhouse effect and global warming. There is a need for an alternative gas that is environmentally friendly, economically viable, and readily available. Hydrogen gas is currently used across various industries and is increasingly considered a potential primary fuel source for the future. In this study, a hydrogen fuel cell was used to produce HHO (brown) gas as a replacement for acetylene through electrolysis. The HHO gas was used to weld a randomly selected test piece, which was then evaluated alongside an acetylene-welded test piece. The integrity of both welds was assessed using dye-penetrant and radiographic testing, showing that welds from both gases were strong. Welding with HHO gas, followed by non-destructive inspection, also proved effective, with any defects attributed to inexperience in welding. The adoption of HHO gas in the welding industry is recommended due to its potential socio-economic benefits, health advantages, and environmental friendliness. Challenges related to initial investment costs may be mitigated as technology advances. Further research should focus on qualitative weld testing, economic and environmental impact assessments, and developing a business model for HHO systems.

## 1.0. Introduction

The welding industry faces challenges, from harsh environments to strict safety regulations. Ensuring welder safety, particularly by minimizing exposure to hazards like fumes and UV radiation, is crucial for prolonging careers (Hamzah, 2023, Shrivastava et al., 2015). Additionally, improved weld accuracy reduces rework and waste, impacting costs significantly, especially in the energy sector where rigorous testing is required. By adopting advanced technologies, such as HHO gas welding, and prioritizing quality control and safety, the welding industry can address these challenges and move towards a more sustainable future (Nabil and Dawood, 2019).

The welding industry has been evolving to meet demands for improved productivity, efficiency and quality. This evolution has mainly be driven by the complex nature of materials produced to provide better functionally specific properties (Paparao and Murugan, 2021).Welding is the primary means of producing and restoring metal products. This process of joining metals or plastic is very reliable, efficient and

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economically viable. Globally welding is a huge income generating fabrication technology that serves myriad of companies and businesses. The current trends in welding in industry have been highlighted in Table 2 (Kah and Martikainen, 2012, Baicun et al., 2020). Welding plays significant role in the construction industry (building and bridges), automotive industry, the energy sector, electronic industry etc. The global welding market is projected to rise from $20.99 billion in 2021 to $28.66 billion in 2028 at a CAGR of 4.6% within the forecast period of 2021-2028 (Market Research Report 2021)

Currently, brazing/welding, and other flame-based industrial processes commonly use highly flammable bottled gases like propane and acetylene. Storing these gases in high-pressure cylinders increases accident risk and raises insurance costs for transportation, facilities, and operators (Yan et al., 2023, Tawfiq et al., 2024). These processes are vital in industries such as oil and gas, transportation, construction, automotive repair, and metalwork, and are often handled by workers in small-scale industries worldwide. They are widely used across various applications through fuel and oxygen flames in hand torches for brazing, fabrication, cutting, and welding (Civjan et al., 2020, Ramesh, 2020).

Acetylene is an extremely unstable gas, which has the ability to decompose vigorously, even in the absence of an oxygen source. This gas might be important and of good service, but it is highly flammable, and its high energy makes it very dangerous. Acetylene decomposes to generate hydrogen and carbon when it is overheated and compressed (Mizutani et al., 2007, Rokstad et al., 2014).

The substantial amount of heat that emanates from the decomposition of acetylene gas generally forms an explosion with greater energy. As a result of these properties, acetylene is commonly stored in special pressure cylinders. These compressed gas cylinders are known to have failed terribly mostly splitting axially and broken off into numerous pieces. Evidence has shown that these fragments can travel 200 m from accident sites (Mirzaei, 2008). It has been identified that the start of decomposition in all accidents is related to the cylinder valve. Acetylene gas in pressure cylinders can also be lethal under fire conditions due to the formation of shrapnel if they explode (Jankuj et al., 2022).

According to the report of the United State Bureau of Labour Statistics, every year, 20 deaths and 6,000 injuries are recorded as results of compressive gas accident such as acetylene gas, argon, propene etc. These risks and accidents make it imperative to find effective measures and alternative to acetylene gas to prevent an explosion (Hooket et al., Rani et al., 2005).

In this study, the authors have developed a more environmentally friendly gas by splitting water into hydrogen and oxygen gas (HHO) via electrolysis of water. The technology uses a portable electrolyser working on one phase electricity supply. The technology uses alkaline water electrolysis which is a well-established technology; commercially available processes to generate the hydrogen and the oxygen gas into two separate streams connected to a flame torch at low pressure. The hydrogen and the oxygen gas generated can be controlled individually and combusted at the point of surface mixed burner by mixing the hydrogen and oxygen (oxy-hydrogen) gas in proportion. This means that the flame chemistry is controlled by the reduction of hydrogen and the oxidation of oxygen in a proportion to conform to the needed application.

The versatility of hydrogen as an energy carrier and its efficiency as a clean fuel enable its utilization in a broad range of applications across several industries (Yuchao et al., 2024, Le et al., 2024). Some primary uses of hydrogen in different sectors are listed in Table 1 (Market Research Report 2006, Vedachalam and Dalai, 2023, Rani et al., 2023, Shakeri et al., 2020, Wei et al., 2022, Chen et al., 2020, Humphreys et al., 2021, Sabat, 2021, Kim et al., 2021, Attah-Kyei et al., 2022, Dolatabadi et al., 2023, Ghimire et al., 2024, Ghirardi et al., 2023, Dolatabadi et al., 2023, Ghimire et al., 2024, Schiro et al., 2020, Billerbeck et al., 2024, Faramarzi et al., 2021, Yang et al., 2023, Lim et al., 2021, Okninski et al., 2021).

Hydrogen production and uses involves a varied array of technologies and applications that make hydrogen a useful and significant energy carrier (Wang et al., 2021, Yang et al., 2024). In a typical alkaline electrolysis technology, direct current is made to pass through the metal electrodes and electrolyte resulting in the generation of hydrogen and oxygen gas. The cathode produces the hydrogen, and oxygen is produced at the anode. Oxy-hydrogen (HHO) is generated when the electrode in the electrolyzer is closely assembled in the electrolyte solution separated by a semi-permeable membrane (Ou et al., 2024, Megía et al., 2021).

Welding gases and fumes have a negative impact on both the environment and the health of the welder (Mehrifar et al., 2019). There is therefore the need for an alternate fuel source for welding. The alternate fuel source should be environmentally friendly, economically viable, and readily available. Oxy-hydrogen gas has unique properties that qualifies it as a sustainable fuel for welding. These properties include amongst others, it burns in one phase whiles oxyacetylene burns in three phases with ozone depleting gases as byproducts. The flame obtained from burning oxy-hydrogen is very pure with excellent heating power (Suban et al., 2001). Despite the fact that oxy-hydrogen technology is particularly successful at minimizing the usage of fossil fuels, its implementation and improvement are still viewed as challenging. Hydrogen gas is used in a range of commercial and industrial applications, and it has the potential to become a significant fuel in the future.

This study would employ the use of a hydrogen fuel cell-dry cell generator in the generation of oxy-hydrogen gas via electrolysis, the oxy-hydrogen produced would be used in welding and the integrity of welds from oxy-hydrogen gas would be tested using NDT techniques.

## 2.0. Methodology

### 2.1. *Production and welding with oxyacetylene gas*

Acetylene gas was produced by reacting calcium carbide with water in a cylinder according to the balanced chemical reaction below (Singh et al., 2020).

$$CaC_{2(s)} + 2H_2O_{(l)} \rightarrow C_2H_{2(g)} + Ca\,(OH)_2\,_{(aq)} \tag{1}$$

The cylinder is covered tightly to prevent the produced gas from escaping. The valve of the acetylene cylinder was opened, to check the pressure of gas produced through flaming. Carburizing flame is thus produced. The oxygen cylinder was opened and regulated to mix with the acetylene gas to form a weldable flame. Images of the production steps are displayed in Fig. 1 and the resulting reaction is as follows:

$$C_2H_{2(g)} + 2O_{2(g)} \rightarrow 4CO_{(g)} + 2H_{2(g)} + \text{heat} \tag{2}$$

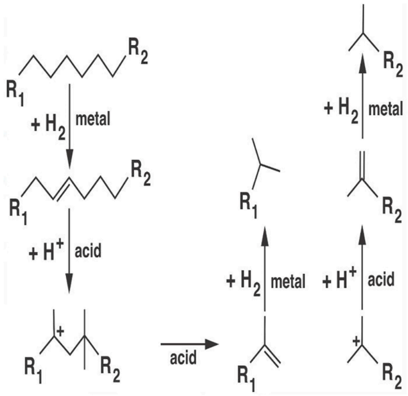
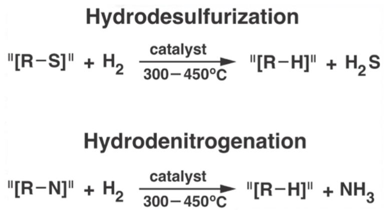
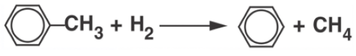
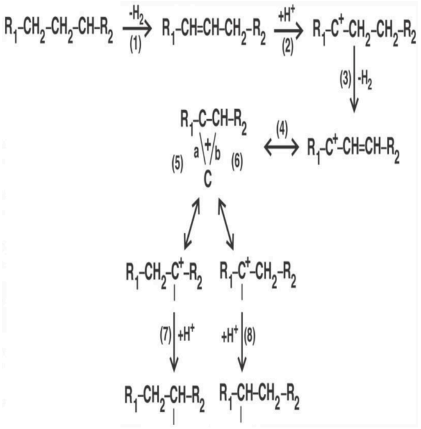
$$4CO_{(g)} + \mathbf{2H_{2(g)}} + \mathbf{3O_{2(g)}} \rightarrow \mathbf{4CO_{2(g)}} + \mathbf{2H_2O_{(l)}} + \textbf{heat} \tag{3}$$

A 1.5 mm thickness test piece was joined together. With the leftward welding method, the flame from the torch nozzle was aimed at the test piece at an angle of 45° and the filler rod at an angle of 30° in the opposite direction, the test piece was welded. The butt weld joint was formed through a beaded appearance. The welded test piece was allowed to cool before it was taken to the laboratory.

### 2.2. *Electrolyzer setup*

Fig. 2 shows three different views of the STWEG-M1 oxyhydrogen gas generator setup used in this work, and Table 3 displays the properties and operating conditions of the STWEG-M1. The mini water decomposition equipment was purchased from Hubei Aison Children Products Co., Ltd. The STWEG-M1 oxyhydrogen gas generator setup is designed and fabricated with transparent acrylic plastic, and its gas generation process is straightforward. The electrolyzer provides high gas production and effective heat dissipation, decomposing water to generate hydrogen and oxygen gas simultaneously, which can be

**Table 1**
Some primary uses of hydrogen in different industrial sectors.

| Application Areas | Production Methods | Reaction | Advantage | Products | **Ref.** |
|---|---|---|---|---|---|
| **Oil Refining** | Hydrocracking breaking of heavy oil fractions into lighter forms |  | Produces high-quality, low-sulphur fuels<br>High yield of valuable lighter products | saturate the cracked hydrocarbons | (Rokstad et al., 2014) |
| | Hydrotreating (Hydrodesulfurization)-Removal of sulfur, nitrogen and other impurities from crude | <br>Hydrodesulfurization<br>$"[R-S]" + H_2 \xrightarrow[300-450^\circ C]{catalyst} "[R-H]" + H_2S$<br>Hydrodenitrogenation<br>$"[R-N]" + H_2 \xrightarrow[300-450^\circ C]{catalyst} "[R-H]" + NH_3$ | Cleaner fuels<br>Low sulfur content, reducing $SO_X$ emission | Hydrocarbons, Sulfide (H2S), Ammonia (NH3) | (Mirzaei, 2008) |
| | Hydrodealkylation - Detaching alkyl groups from aromatic hydrocarbons |  | Enhances the production of petrochemical products | Benzene, Toluene, Xylene etc. | (Jankuj et al., 2022), (Hooket et al.) |
| | Hydroisomerization - Removal of metal fractions from Crude oil |  | Prevents metal impurities from distracting catalytic activities<br>Protect refining equipment | Pure hydrocarbons | (Rani et al., 2005), (Yuchao et al., 2024) |
| **Ammonia Production** | Haber-Bosch Process - | $N_2+3H_2\rightarrow 2NH_3$<br>The process typically operates at pressures of 150-250 atmospheres and temperatures of 400-500°C in the presence of a catalyst | | Fertilizers, Chemical Industry | (Le et al., 2024) |
| **Steelmaking and Non-Ferrous Metal Production** | Reduction of iron ore (iron oxide) to iron<br>Hydrogen plasma is used to reduce iron ore directly | $Fe_2O_3 + 3H_2 \rightarrow 2Fe + 3H_2O$. | Significantly reduces CO2 emissions<br>Produces high-purity iron | Potentially higher efficiency and lower emissions | (Market Research Report 2006), (Vedachalam and Dalai, 2023) |
| | Non-Ferrous Metal Production - Reduces metal oxides to their respective metal | $WO_3+3H_2\rightarrow W+3H_2O$ | Produces high-purity metals. | | (Rani et al., 2023) |
| **Concrete Production** | Hydrogen as a Fuel Source - cement kilns | Hydrogen is used a heating fuel in the limestone ($CaCO_3$) to produce clinker instead of fossil fuel | Process produces only water vapor and heat, reducing CO2 emissions | | (Shakeri et al., 2020), (Wei et al., 2022) |
| Energy Storage | Hydrogen in Energy Grids - Balancing grid - electricity production for later use | Hydrogen absorbs excess energy during periods of low demand and releases it when demand is high | Helps balance supply and demand in grid with variable energy mix | | (Chen et al., 2020) |

(continued on next page)

**Table 1** (*continued*)

| Application Areas | Production Methods | Reaction | Advantage | Products | **Ref.** |
|---|---|---|---|---|---|
| | Hybrid Energy Systems - Integration of hydrogen storage with renewable energy | By converting excess renewable energy into hydrogen | Enables the creation of hybrid systems combining solar, wind, and hydrogen storage to achieve higher reliability and efficiency. | | (Humphreys et al., 2021) |
| | Backup Power - Hydrogen fuel cells | During power outages, Hydrogen fuel cell is used to convert hydrogen into electricity by electrochemical process. | Provide reliable backup power for data centers, hospitals, and telecommunications. | | (Sabat, 2021) |
| **Heating and Cooling** | Hydrogen for Heating - Hydrogen boilers | Hydrogen boilers operate similarly to natural gas boilers but burn hydrogen to produce heat | Zero carbon emissions from combustion | | (Kim et al., 2021) |
| | Hydrogen in Heat Pumps - | Hydrogen heat pumps use hydrogen as an energy carrier to drive the heat pump cycle, which transfers heat from one place to another | High efficiency in both heating | | (Attah-Kyei et al., 2022) |
| | Hydrogen for Cooling - Hydrogen in Refrigeration Cycles | Hydrogen can be used in refrigeration cycles, such as absorption refrigeration, where it acts as a refrigerantt | Can be powered by heat sources, including waste heat from industrial processes | | (Attah-Kyei et al., 2022), 30] |
| Food Industry | Edible Oil Hydrogenation | Hydrogen is used in a chemical process to convert liquid vegetable oils into semi-solid or solid fats. This is done in the presence of a catalyst mostly nickel. | Hydrogenation increases the oil's resistance to oxidation, reducing rancidity and extending shelf life. The process also alters the physical properties of the oil, making it suitable for margarine, shortening, and baked goods. | | (Ghimire et al., 2024) |
| Space Exploration | Rocket propulsion | Hydrogen in the form of liquid hydrogen (LH2) is used as a propellant. When combined with liquid oxygen (LOX) as an oxidizer, it forms one of the most efficient rocket fuels available, known as a cryogenic propellant combination. | When liquid hydrogen combusts with liquid oxygen, it releases a significant amount of energy, producing water vapor as a byproduct. This reaction is highly energetic and efficient, contributing to powerful thrust. | | (Ghirardi et al., 2023) |
| Metal processing and Welding | Metal Reduction | $Fe_2O_3 + 3H_2 \rightarrow 2Fe + 3H_2O$.<br>. | Using hydrogen instead of carbon (such as coke in traditional blast furnaces) significantly reduces carbon dioxide emissions, contributing to cleaner industrial processes. | | (Dolatabadi et al., 2023) |

directly ignited. The STWEG-M1's gas generation process is pollution-free, consuming only water and electricity, with water easily added when the level drops. During operation, the operator must wait 30 seconds before igniting the produced gas. While in use, the spray gun should remain open, and the power supply to the electrolyzer should be turned off before closing the valve. The flame produced is extremely hot and should not be touched by hand.

### 2.3. *Production and welding with oxy-hydrogen gas*

A series of 1L volume of 0.25 M of the electrolyte (Potassium Hydroxide (KOH)) was prepared by dissolving 14.03 grams of Potassium Hydroxide granules in 1L- deionized water. About 3.5 L of the electrolyte prepared was transferred into the electrolyzing chamber through the copper inlet tube. The rubber tube connecting the electrolyzing chamber and the bubbler chamber was then attached. About 0.5 L volume of deionized water was poured into the bubbler chamber. After checking for proper tightening of the opening, the 12 V power source was supplied to the terminals of the fuel cell. As the unidirectional current starts flowing through the plates, they get energized and the process of electrolysis begins. The gaskets offer excellent resistance to the leakage of the electrolyte. The electrolyzing chamber heats up as it is an exothermic reaction. Dissociation of water molecules takes place leading to the formation of oxygen and hydrogen gas on the positive and negative electrodes respectively with the aid of the electrolyte. The resulting reaction is as follows:

$$\textbf{Electrolyte: } H_2O \rightarrow H^+ + OH^- \tag{4}$$

$$\textbf{Electron-withdrawing cathode: } 2H^+ + 2e- \rightarrow H_2 \tag{5}$$

$$\textbf{For the anode, we have } 4OH^- \rightarrow O_2 + 2H_2O + 4e \tag{6}$$

Hermetically sealed fuel cell allowed for the gas to be directed through the rubber tube to the bubbling chamber and displaced to the torch. The gas coming out of the nozzle was torched and the valves regulated, to which weldable flame was formed also known as the blue flame, to show the presence of oxygen and hydrogen gas. The weldable flame was later used to weld and braze metal pieces. The test pieces joined together at a flame angle of 45° from the torch nozzle was directed on the test piece and the filler rod at an angle of 30° caused spark flames of light in the opposite direction using the right welding method due to the thickness of the test piece (Fig. 4). The butt weld joint was formed through a beaded appearance; the brazing was done with the aid of a flux rod and granular flux of the metals. After which the welded test piece was cooled and taken to the laboratory for inspection.

**Table 2**
Current state of welding technologies (Kah and Martikainen, 2012, Baicun et al., 2020).

| Type of welding technology | Current state | Advantage | Disadvantage |
|---|---|---|---|
| Gas welding/ oxyacetylene welding | It uses flame produced by oxygen and acetylene for welding. | It is used in welding thinner metals<br>Metals used could be ferrous, non-ferrous, alloy steel, carbon steel, etc. | -Produces very high heat (about 4500-degree Fahrenheit) |
| Intelligent welding systems (IWS) | It has been applied to welding systems to more actively monitor and control welding dynamics and quality. | Work efficiency, quality and stability are improved | -Generalized machine learning (eg. Performing the full range of hum cognitive abilities) is a long way off. Machine learning can only replace human intelligence at reasonable points |
| Gas metal arc welding (GMAW) | it has evolved to allow better arc control, better bead contour control and better deposition control | -It can join metals of different thicknesses.<br>- Components of welding are readily available. | -It always needs a bottle of gas for shielding.<br>-Welding cannot be done outside. |
| Submerged arc welding (SAW) | It is limited when welds made out of positions or when several short welds are required on many pieces involving frequent moves of the welder and the workpiece | -The method is used in welding metals with thicknesses up to 100 mm.<br>-It has a high deposition rate of 20 Kg/hour. | -The welding process is mechanized and is burned under granular flux, so it cannot be seen outside. |
| Gas tungsten arc welding (GTAW) | It is evolving to allow reactive metals like titanium (Ti) to be welded or repaired in the field | -Welds are precise and have a neat appearance.<br>-Welds are durable and of high quality. | -This welding type is complex and requires a great deal of expertise. |
| Flux cored arc welding (FCAW) | Lower filler metal utilization and higher filler metal costs will keep it from growing fast. | -It can be used outdoors without gas shielding<br>-Metal piece for welding does not need pre-cleaning and welding can be done in any position | -Produces a lot of smoke which can be carcinogenic.<br>-Electrode used can be very expensive. |
| Laser beam technology | It is extensively used in automobile fabrication and processing plastics. However, it can only be used for material thickness below 25mm. | -Welds made by this process are precise and of high quality. | -welding can be done only in a special vacuum atmosphere. |
| Friction and resistance welding | It is used in rail vehicle and aerospace Processes industry. It has low stability of rotating tools. | -Produces high quality welds. | -Equipment used can be very expensive and the working process may not be possible for all parts. |

### 2.4. *Test integrity (Chassignole et al., 2010, Deepak et al., 2021)*

#### 2.4.1. *Visual inspection*

All test pieces were visually inspected for welding flaws with the naked eye before being transferred to the lab for non-destructive testing. This initial inspection allowed for easy identification of any surface flaws and an evaluation of the joint's overall appearance.

#### 2.4.2. *Dye penetrant testing*

The methodology for penetrant testing includes pre-cleaning, applying the penetrant, removing excess penetrant, applying the developer, performing a visual inspection, and post-cleaning. Dye Penetrant Testing is a non-destructive testing method used to detect surface defects in metals, such as mild steel.

*2.4.2.1. Pre-cleaning of surface of test piece.* Dirt, grease and oil on the surface of the mild steel used in this study was removed with a piece of cloth to ensure that potential defects are open to the surface and to allow the dye to penetrate effectively. After cleaning, the surface was allowed to dry thoroughly to remove any residual moisture.

*2.4.2.2. Application of Dye penetrant and Removal of excess penetrant.* At a distance of 30 cm and at a 45° angle along the beaded region of the test piece, a visible penetrant water-washing spray was applied to the surface, ensuring full coverage, especially over areas likely to have flaws. The dye penetrant was allowed to remain on the surface for 15–30 minutes to enable it to fully penetrate any surface-breaking flaws. Excess penetrant was then removed from the test sample with a clean, dry towel and a solvent remover. The surface of the test piece was subsequently subjected to flash heating for one to two minutes to allow any remaining solvent to evaporate. Care was taken during cleaning to avoid removing penetrant from defect areas

*2.4.2.3. Application of developer.* A non-aqueous developer (Fig. 5a) was sprayed at the same angle as the penetrant over the beaded region of the test piece (See Fig. 5b). The developer is allowed to stay on the surface for 10 – 30 minutes to ensure that the developer pulls out the penetrants confined in the defects, making them visible.

*2.4.2.4. Visual inspection.* After the test sample dried following the development procedure (see Fig. 5c), a visual examination was conducted under adequate lighting, and a report was compiled based on any faults or defects discovered.

### 2.5. *Radiography testing*

The surface preparation of the test piece was obscured by imperfections or false indications. All butt-welded seams required cleaning to match the finish of the base material. A gamma-ray radiation source (IR-192) device was set up (see Fig. 6). The test piece, along with the Penetrameter (IQI), was neatly taped in place between the guide tube tip, the cassette, and the test piece. A survey meter was used to detect any radiation exposure around the device. The radioactive source was then released from the camera through the guide tube, exposing the test piece for approximately 5 minutes. After exposure, the active source was returned to the camera. The film was then carefully removed and immediately transferred to the darkroom for processing.

### 2.6. *Manual film development*

The imaging modality employed for this outcome is analogous to developing film in a dark room, where adjustments are made manually. With its surface shielded from light, the film was safely handled by relatively clean, dry hands.

In the darkroom, open tanks served as the processing medium. The

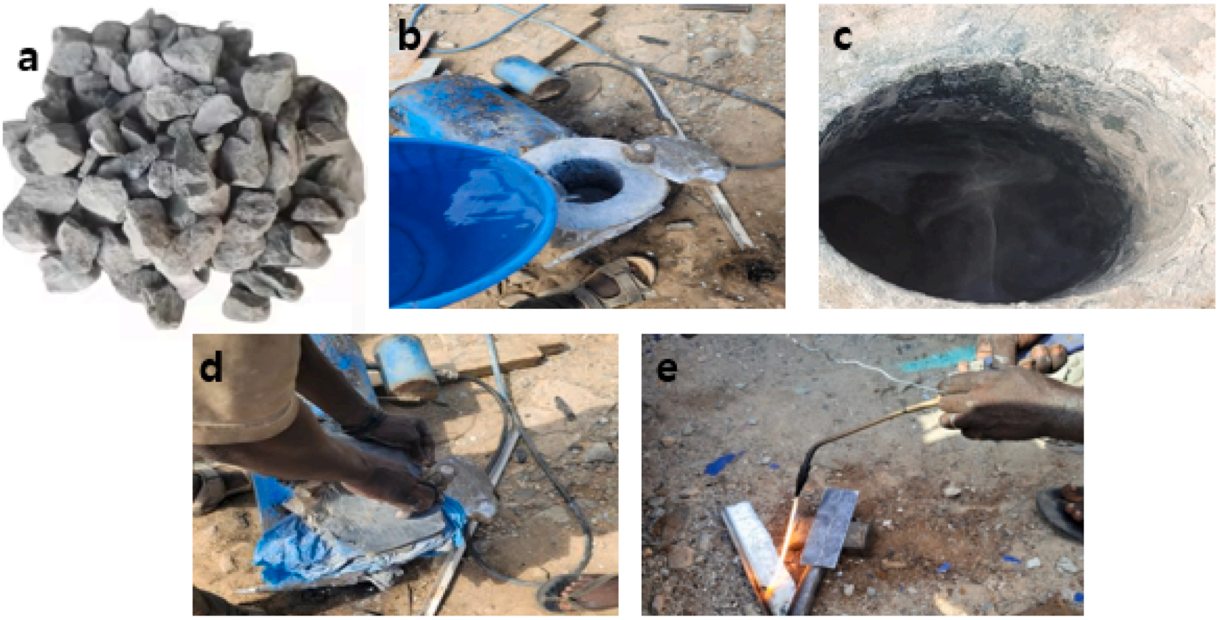


**Fig. 1.** Image of (a) commercially available calcium carbide (b) Reacting calcium carbide with water (c) Production of acetylene gas (d) Covering of cylinder (e) Opening of the acetylene tube valve control pressure.

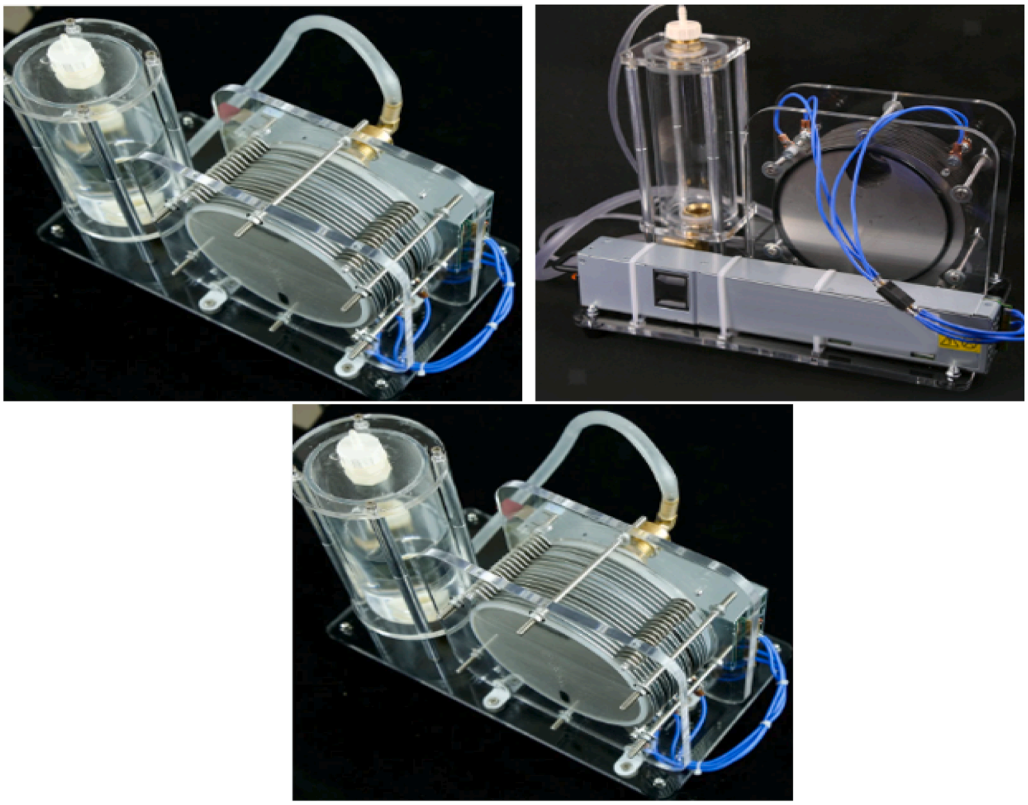


**Fig. 2.** Different view of the STWEG-M1 oxyhydrogen gas generator set-up.

tank contains two solutions for both the developer and the fixer. Before the process of development could commence, the film had to be removed from the cassette and placed on a hanger. Meanwhile, the solution must be mixed in the tanks. The film hanger was placed in the developing tank and agitated every 30 seconds in two different directions for roughly five minutes at 20 degrees Celsius. Temperature influences the rate of advancement of a process. Developer activity persisted in the emulsion after the development process was completed. The developer activity in an acid stop bath tank may be neutralized by aggressively washing and churning the emulsion in clear water for around two minutes per 30 seconds. In order to obtain a speedy and uniform fixation in the fixer tank, the hanger must be vertically agitated for thirty seconds. The required repair work in the fixer tank was finished in approximately ten (10) minutes. After finishing a portion of the washing process with clean

**Table 3**
Operating condition of fuel cell used in this study.

| Model | STWEG-M1 |
|---|---|
| Gas Type | Mixed hydrogen and Oxygen |
| Electrode Material | 316 Stainless steel which is an alloy of chromium, nickel and molybdenum |
| Torch setting | Medium- high (adjusted depending on the material thickness, gas flowrate and electrode type) |
| Working Voltage | 12 V |
| Electrical current | 10 amps |
| Power | 200 Watt |
| Pressure | 1 atm |
| Temperature | 30 – 60 $^oC$ |
| Gas generation | 1333 ml/minute (2/3 hydrogen, 1/3 oxygen) |
| Electrolyte used | Potassium Hydroxide (KOH) |
| Electrolyte Concentration | 0.25 M |

water in the first clean washer tank, the load was moved to the second clean washer tank within two minutes for both tanks in order to complete a full rinse with clean water. By completing these procedures, any remaining chemicals on the film will be erased. The film was then taken from the hanger, dried in a dryer, and placed beneath a radiographic film viewer to observe the results. A light box was deployed in order to facilitate comprehension of the subject.

### 2.7. Assessment of welds

The welds were assessed using visual inspection after penetrant testing was performed on both welds, and also radiography testing was performed and inspected. The visual inspection was done to identify the flaws which were to appear after the welding.

## 3.0. Results and discussions

### 3.1. Production of oxyhydrogen gas

The condition for the mixed gas (hydrogen + oxygen) generation in the electrolyzer is displayed in Table 3. The electrolyzer is shown in Fig. 3a. The stacked electrodes (made of stainless steel) in the electrolyser are where electrolysis process happens, producing hydrogen and oxygen from water. In the electrolyzer system, flow of water to each electrode in the stack is essential to ensure optimum performance. The water circulating in the electrolyzer should be sufficient enough to carry the produced gases out of the cells. The water in the cells is also responsible for the control of the temperature of the stacked electrodes.

### 3.2. Welding using oxyacetylene and HHO gas

For welding with oxy-hydrogen, mild steel (ASTM A36) was used for the testing. The summary of the chemical, physical and mechanical properties of the galvanized steel (ASTM A570 Steel, grade 40) used in the study is shown in Table 4. It has excellent welding properties and used in many fabrication and construction projects. It works perfectly with any welding method and the produced joints are of exceptional qualities. Fig. 7 shows a typically welded specimen using oxy-acetylene (7a) and oxy-hydrogen (7b). From the images, complete and excellent fusion can be observed in welded areas of the samples employing both oxyacetylene and oxy-hydrogen gas. Furthermore, the samples looked perfectly welded with the application of less filler rod. In welding with acetylene gas, the stages involved are described in the eq. 1 and 2. In the first stage, acetylene is converted in the presence of oxygen to carbon monoxide and hydrogen gas. Heat is released as a result.

$$\mathbf{C_2H_2 + 2O_2 \rightarrow 4CO + 2H_2 + Heat} \qquad \text{(Eq. (1))}$$

$$\mathbf{4CO + 2H_2 + 3O_2 \rightarrow 4CO_2 + 2H_2O + Heat} \qquad \text{(Eq. (2))}$$

In the second stage, carbon monoxide and hydrogen react with oxygen to produce carbon dioxide and water vapour.

In comparison with oxy-hydrogen welding, the by-product in the burning of oxy-hydrogen is environmentally friendly; water and heat (See eq. 3).

$$H_2 + 2O_2 \rightarrow 2H_2O + \text{Heat} \qquad \text{(Eq. (3))}$$

The flame produced from the reaction of oxy-hydrogen are

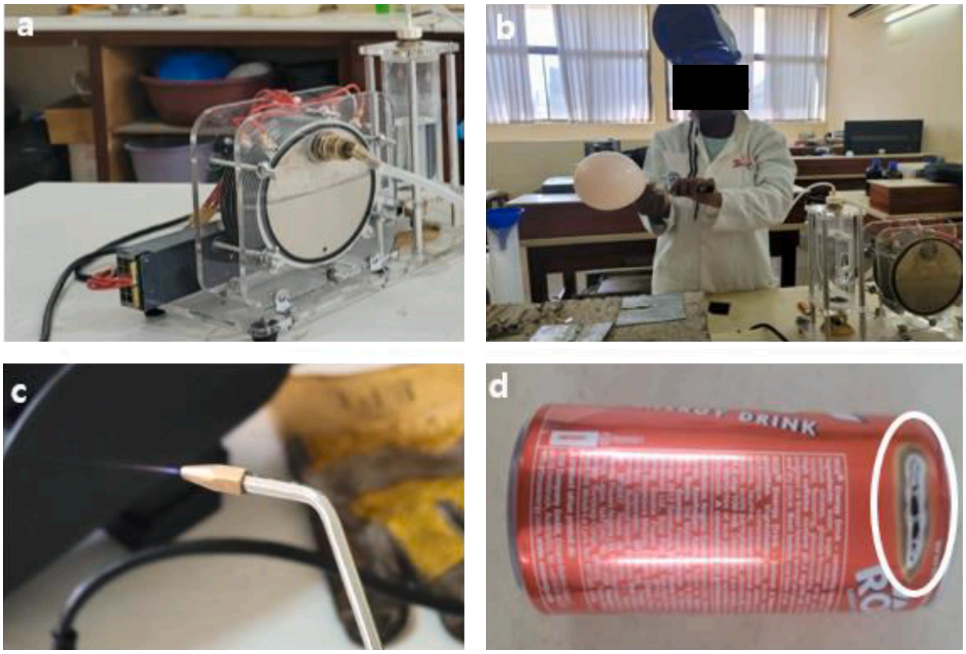


**Fig. 3.** Images of (a) the complete setup of the fuel cell containing the electrolyte and deionized water for displacement, (b) inflating balloons with the produced gas, (c) normalized flame (blue flame) for welding, and (d) a cut can using HHO gas.

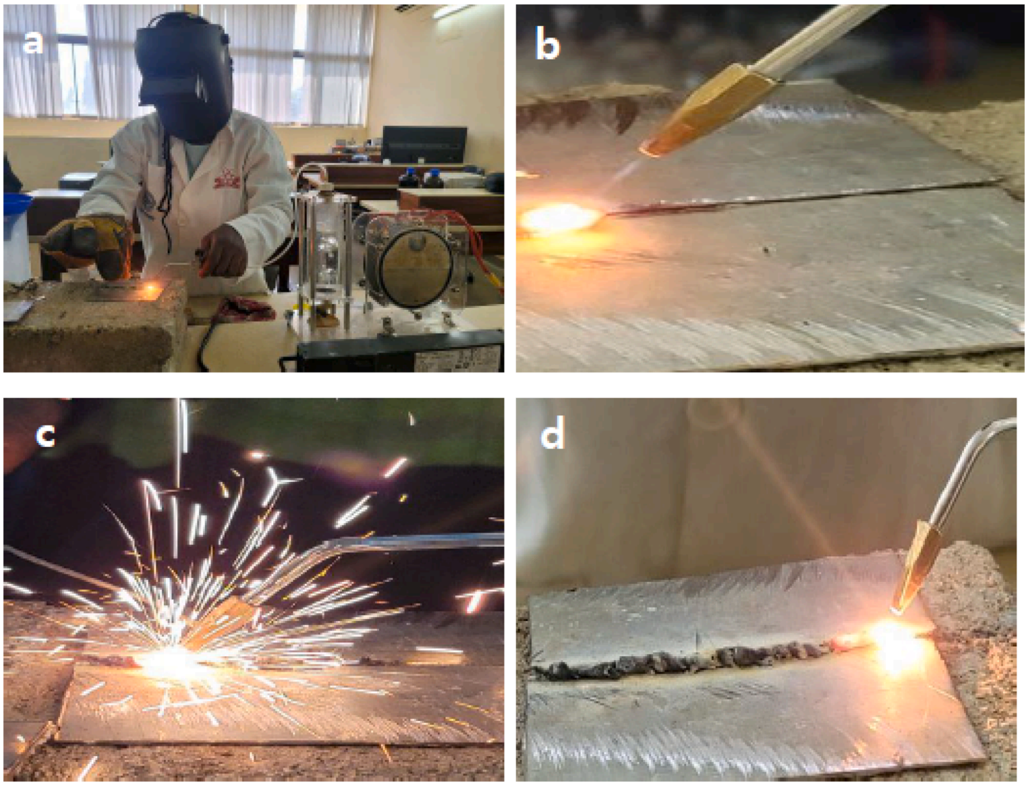


**Fig. 4.** Images of (a) welding with HHO gas, (b) joining the test piece with a weldable flame, (c) spark flame with the introduction of filler metal, and (d) appearance of beads on the test piece during welding with HHO gas.

**Table 4**
Chemical, physical and mechanical properties of galvanized steel.

| **Chemical Composition** | | | | | | |
|---|---|---|---|---|---|---|
| Element | Carbon (%) | Copper (%) | Iron (%) | Manganese (%) | Phosphorus (%) | Sulfur (%) |
| Content | < = 0.25 | 0.20 | 99.00 | < = 0.90 | < = 0.04 | < = 0.05 |
| **Physical Properties** | | | | | | |
| | | | Metric | | Imperial | |
| Density | | | 7.80 g/cm$^3$ | | 0.282 lb/in$^3$ | |
| **Mechanical Properties** | | | | | | |
| | | | Metric | | Imperial | |
| Tensile strength, Ultimate | | | 380 MPa | | 55100 psi | |
| Tensile Strength, Yield | | | 275 MPa | | 39900 psi | |
| Elongation at Break | | | 14 - 16 % | | 14 – 16 % | |
| Elongation at Break (in 50 mm) | | | 23.0 % | | 23.0 % | |
| Bulk Modulus (typical for steel) | | | 160 GPa | | 23200 ksi | |
| Shear Modulus | | | 80.0 GPa | | 11600 ksi | |

characterized by flame temperature (2800 °C). Welding with oxyacetylene goes through two reaction steps while oxy-hydrogen is involving one step. Aside from the purity of oxy-hydrogen flame, it is also endowed with excellent heating power and high resolution which facilitate precise and quality welding to be done (Attah-Kyei et al., 2022). The welding process using the two oxyfuel share some similarity; they both involve portable equipment; that are easy to carry around. The user of the flame has control over the rate of heat output. On the other hand, in oxyacetylene welding, the energy essential for welding requires acetylene and oxygen gas and both gases requires cylinder for storage (Parkin and Flood, 2013). Again the production of oxyacetylene gas requires coke and lime from the natural environment to produce acetylene gas for welding (Zhang et al., 2021).

### 3.3. *Assessment and test integrity*

Non-Destructive Testing (NDT)

Non-destructive Testing (NDT) is employed to inspect and test the manufactured, fabricated components for their characteristics and flaws. NDT can be used on different types of materials including composite materials. This technique detects internal, surface, and subsurface defects and guarantees quality of products and joining processes without destroying them. It ensures array of inspection methods that allow components, systems and materials to be inspected for proper maintenance to avoid catastrophic accidents. There are different methods involved in NDT. The most common ones include visual inspection, ultrasonic NDT, radiographic NDT, leak testing, dye penetrant testing etc. Some of these methods allow for surface inspection, while others allow for complete volumetric inspection of the material or system.

### 3.4. *Visual inspection*

This method is the most basic way of examining systems, materials of components without destroying samples. The welded samples were assessed using visual inspection, after penetrant testing and radiography testing was performed on both welds. The visual inspection was to identify the flaws which were to appear after the welding. By visual inspection, it can be observed that the two-welding processes yielded no cracks or defects along the whole length of the joint (See Fig. 7a and 7b).

### 3.5. *Dye penetrant radiography testing*

The dye penetrant and radiography testing were also done following their required procedure without any interference. Table 5 depicts the results of the dye penetrant inspection. In the dye penetrant testing, the absence of leakage or stain from penetrant is an indication of an excellent weld and the opposite is true. The method is based on capillary action. The test piece is sprayed with a low viscous liquid dye (See

**Table 5**
Results of the dye penetrant test by visual inspection.

| Test Sample | Observation | NDP (DPT) Result |
|---|---|---|
| Oxyacetylene welded sample | No cracks | Acceptable |
| Oxy-hydrogen welded sample | No cracks | Acceptable |

Fig. 5b). The liquid dye is sucked into any cracks or flaws in the welding due to its low viscosity. Fig. 8 shows sprayed and dried acetylene weld and oxy-hydrogen weld sample pieces, respectively. The parts labelled (A & C) shown in Fig. 8a and Fig. 8b respectively, showed that welding was properly done with no defect of welds indicated after the testing, but the parts labelled (B & D) in Fig. 8a and 8b, proved that the welds were not done well at the ends of the metal so there was some capillary action taking place due to some excessive penetration, rough appearance, and porosity.

### 3.6. Radiography testing

In radiography testing, radiation is directed from the radioactive isotope or an x-ray generator through the material or component being tested and then directed on a film or a detector. A shadowgraph is developed from the detector which will reveal the underlying aspects of the inspected material. The radiography testing reveals aspects of materials or components that are really difficult to detect with the naked eyes. With the radiography testing, a good weld will not show any dark portion or line in the film but a bad weld will show a dark portion or line in the film. The x-ray exposure parameters used for oxyacetylene and oxy-hydrogen gas welded pieces are tabulated in Table 6 and the photographic film images are shown in Fig. 9. The test evaluation results are shown in Fig. 8a for the acetylene weld test piece and Fig. 8b for the oxy-hydrogen welded test piece. The radiographic image was good but it shows a defect called stop-start indication at A in Fig. 9a and Fig. 9b shows a lack of fusion in indication B. The stop-start indication defects in welding occurs when there is discontinuities or imperfections during welding at the start and stop points of a welded seam. This result is attributed mostly to the welder' skills indications and not because of the gases used. Stop and start indications are a necessary aspect of welding. However, their negative effects can be minimized through procedures such as precise manual welding and optimized weld data settings for semiautomatic and automated welding processes. (Turski et al., 2012).

### 3.7. Potential impact of adopting HHO

On the other hand, the adoption of HHO gas for welding has several remarkable impacts across various welding industries. HHO gas, generated by the electrolysis of water, is highly flammable and capable of reaching high temperatures, making it suitable for certain welding applications. Table 7 outlines the impact of adopting oxyhydrogen gas in the welding industry compared to oxyacetylene gas (Suban et al., 2001, Okay Energy Equipment Co., Ltd 2021).

### 3.8. Challenges associated with adopting HHO

The main limitations and challenges in adopting HHO gas welding in industry include the high initial investment cost for electrolysis systems used in on-demand HHO production, which may deter smaller companies from adopting this clean technology. Additionally, electrolysis

**Fig. 6.** Picture Showing the Radiography Testing Setup.

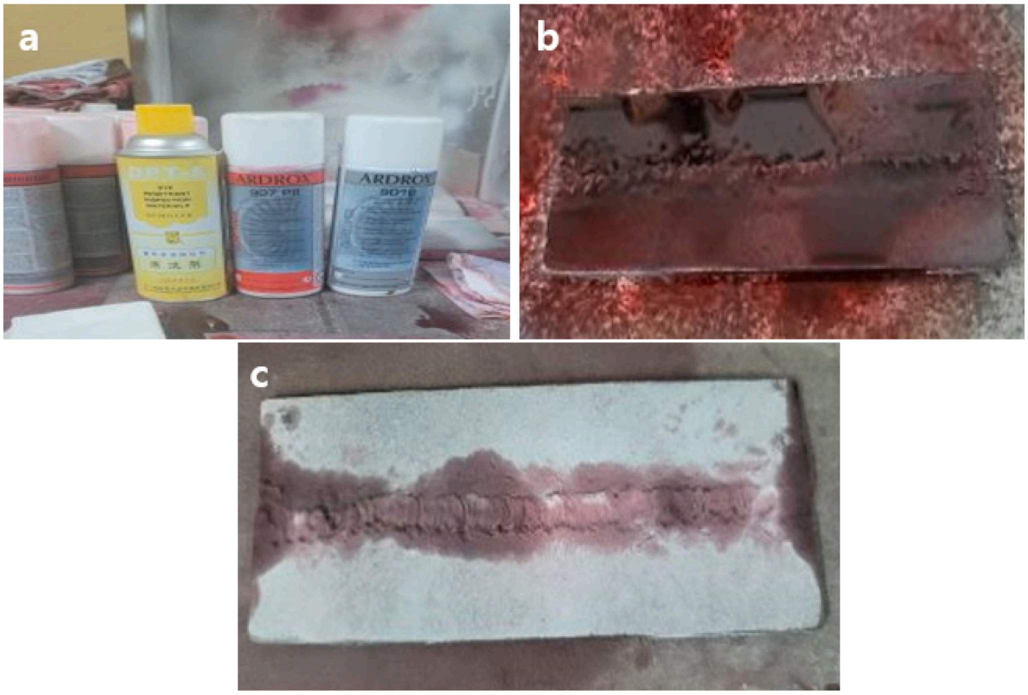


**Fig. 5.** (a) Non-aqueous developer spray, (b) Sprayed welded piece, and (c) Drying up of the developer on the welded piece.

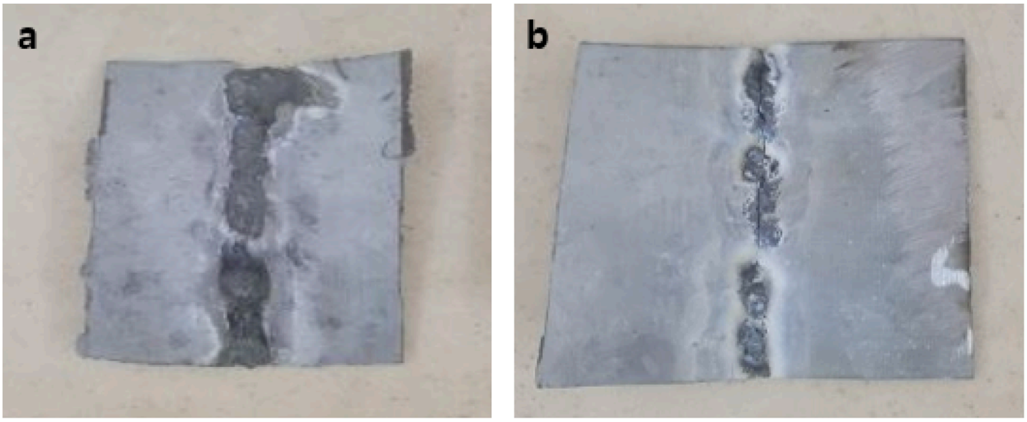


**Fig. 7.** Images of welded pieces using (a) oxyacetylene gas (b) HHO gas.

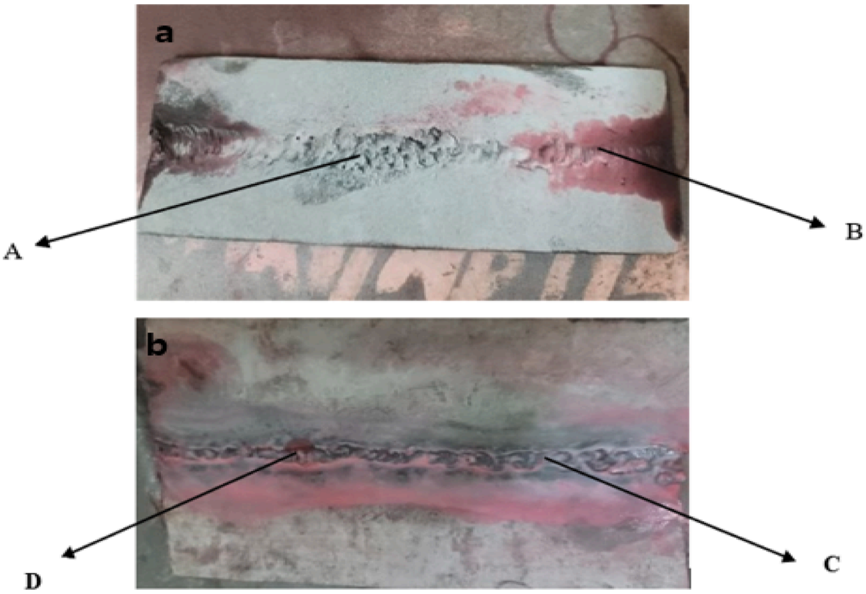


**Fig. 8.** Images showing results of (a) acetylene weld dye penetrant test (b) oxy-hydrogen weld dye penetrant test.

**Table 6**
Radiography exposure parameters of metal welded Joints.

| Parameters | Measure |
|---|---|
| Acceptance Standard | ASME VIII DIV. 1 |
| IQI | 10 FE EN |
| Film | Kodak mx126 |
| Source/Strength | 20 Cu Ir 192 |
| Intensifying Screen | Lead |
| FFD/SFD | 25 ± 1 cm |
| Thickness of galvanized Steel | 1.5 mm |
| Exposure Time | 35 second |

systems require regular maintenance to ensure reliable efficiency and performance, which can add to operational costs. Integrating HHO systems with conventional welding setups may require upgrades or adjustments, introducing complexity and potential additional expenses. Facilities may also need to train and build the capacity of employees to operate these systems safely and efficiently to accommodate the new technology. For large-scale welding operations, continuous HHO gas production may be necessary, which could strain the capacity of electrolysis systems. This limitation currently restricts HHO adoption in industries with high-volume, continuous welding needs unless technological advancements enhance production capacity. Despite these challenges, adopting HHO gas in the welding industry could yield significant economic and environmental benefits, as well as improvements in safety and weld quality. While initial costs and production limits present obstacles, advances in technology could reduce these limitations, making HHO a more practical option for broader industrial use (Subramanian and Ismail, 2018, Ahad et al., 2023).

## 4.0. Conclusions

This study aimed to explore oxyhydrogen gas as a sustainable alternative to oxyacetylene gas for metal welding. Oxyhydrogen gas was generated from an electrolyzer and then used to weld a metal test piece. The integrity of the welded samples was assessed using visual inspection, dye penetrant testing, and X-ray radiography. Both the oxyacetylene and oxyhydrogen gas welding processes achieved complete weld penetration with no microstructural defects. Visual inspection of the oxyhydrogen welds indicated no visible defects. The dye penetrant tests conducted with both oxyfuels were successful and revealed no root defects in any of the samples welded with either fuel. Test components were welded using both acetylene gas and HHO gas, with both gases proving to be effective. Non-destructive evaluation showed that welds produced by both gases were intact and exhibited favorable characteristics. Additionally, compared to oxyacetylene gas, oxyhydrogen

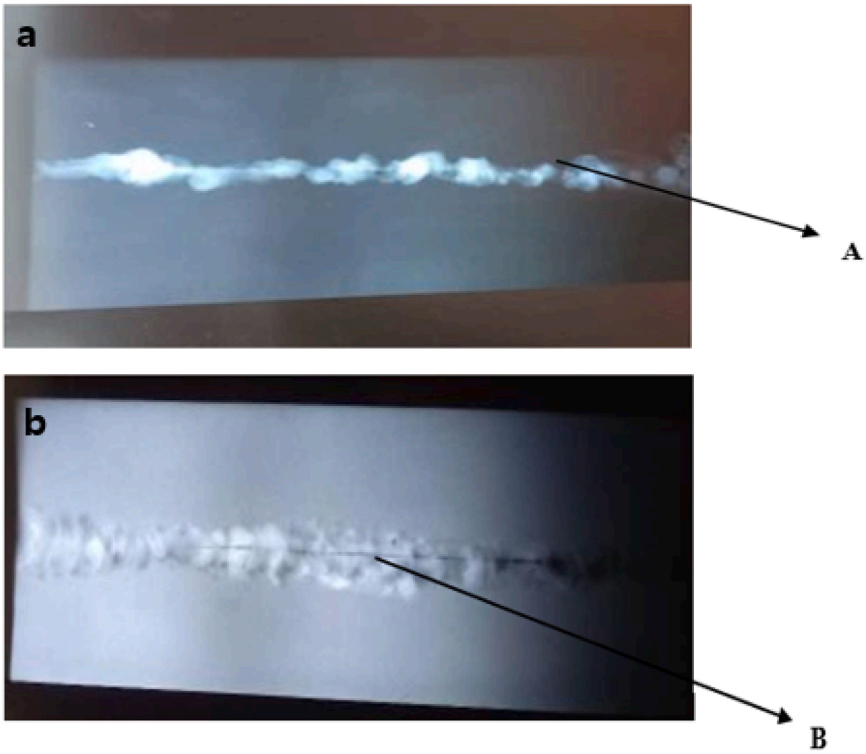


**Fig. 9.** Images of developed film from (a) acetylene weld test piece (b) oxy-hydrogen welded test piece.

**Table 7**
Comparison of oxyhydrogen and oxyacetylene gas in the welding industry (Suban et al., 2001, Okay Energy Equipment Co., Ltd 2021).

| SN | Comparison | Oxyacetylene welding | Oxyhydrogen welding |
|---|---|---|---|
| 1 | Environment and health impact | By product from welding include toxic gases such as carbon dioxide carbon monoxide, and sulfur dioxide.<br>These gases are dangerous to the workers and contributor to climate change | Zero carbon emissions routes. Energy for welding comes from water.<br>Product for combustion is water vapour.<br>By product is non-toxic to the workers and very friendly to the environment. |
| 2 | Safety issues | Gas cylinders, with risk of leakage and explosion<br>Gas leak will lead to poisoning or death | There is no need for cylinder for storage.<br>There is no explosion, leakage, and any other issues with regard to gas cylinder |
| 3 | Operational features | Requires coke and lime to produce acetylene gas for the production of oxyacetylene gas production for welding. | The process consume only electricity and water to produce oxyhydrogen gas.<br>Produce gas on demand.<br>Welding is quick, high accuracy, and smooth |
| 4 | Quality of Welded Material | The flame has a temperature of about 3,200 °C<br>Produced flame is scattered<br>Welded material are covered with black spot. | The flame has a temperature of around 2800 °C<br>Flame concentration is focused<br>There is no carbide production (No black spot) |
| 5 | Economic Impact | Moderate cost on small to medium jobs, but expensive on large jobs | Though initial setup can be high, the continuous operation requires only water and electricity and no other fuel cost<br>40%-60% savings on energy compared to other |

produces a neutral flame that does not require an external oxygen source. It does not emit harmful gases, making it safe for indoor use without posing a risk to the operator. The oxyhydrogen welding process is environmentally clean and has significant advantages over other heat sources. For industrial scale-up and broader adoption, an in-depth techno-economic and environmental impact analysis is required.

## CRediT authorship contribution statement

**Juliet Attah:** Writing – review & editing, Writing – original draft, Methodology, Funding acquisition, Conceptualization. **Latifatu Mohammed:** Writing – review & editing, Writing – original draft, Supervision, Methodology, Data curation, Conceptualization. **Andrew Nyamful:** Writing – review & editing, Resources, Methodology, Data curation, Conceptualization. **Paulina Donkor:** Methodology, Data curation, Conceptualization. **Anita Asamoah:** Supervision, Resources, Methodology. **Mohammed Nafiu Zainudeen:** Resources, Conceptualization. **John Adjah:** Writing – review & editing, Formal analysis. **Charles K. Klutse:** Resources. **Sylvester Attakorah Birikorang:** Resources. **Frederick Agyemang:** Writing – review & editing, Resources. **Owiredu Gyampo:** Supervision, Resources.

## Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

## Data availability

Data will be made available on request.

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