Effect of Pure CO₂ and CO₂-Argon Mixture Shielding Gases on Defects, Hardness, and Penetration in AH-36 Steel Welding

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**Abstract.** This study aims to evaluate the effect of using pure CO₂ and a CO₂-Argon gas mixture (MIX) as shielding gases on the weld quality of AH-36 steel using the Flux Cored Arc Welding (FCAW) process. Weld quality was assessed based on three key aspects: surface defects, hardness, and penetration depth. The methodology included Non-Destructive Testing (Dye Penetrant Test) to detect surface defects, Micro-Vickers hardness testing at three zones (weld metal, base metal, and heat-affected zone), and macrographic analysis to measure weld penetration. Results from the penetrant test indicated that both shielding gases produced acceptable welds with no surface defects, in accordance with ASME Section VIII Division I standards. Hardness testing revealed that the use of MIX gas resulted in higher hardness values, particularly in the HAZ (223.277 HVN) and weld metal (243.624 HVN) zones, compared to the lower values observed with pure CO₂. The lower hardness in the CO₂ welds is attributed to higher heat input and thermal effects. Macrostructure analysis further showed that the MIX gas produced deeper weld penetration (2.997 mm) than pure CO₂ (2.944 mm), indicating better arc stability and reduced oxidation. These findings suggest that MIX shielding gas enhances both mechanical and metallurgical properties in FCAW of AH-36 steel.

# INTRODUCTION

In the modern manufacturing and construction industries, welding plays a vital role as a permanent method for joining materials [1][2]. One of the commonly employed welding techniques in heavy industrial sectors such as shipbuilding and offshore structures is Flux Cored Arc Welding (FCAW) [3]. This method is widely recognized for its ability to improve work efficiency and provide deep weld penetration [4]. However, the quality of the weld is highly influenced by various parameters, one of which is the type of shielding gas used [5]. Shielding gas significantly affects the mechanical properties, surface appearance, and potential defects of the weld joint [6]. For structural materials such as AH-36 steel, which is commonly used in the marine industry due to its strength and durability, the selection of shielding gas becomes a critical factor [7].

In practical welding applications, especially among professional welders, differing opinions often arise regarding the effectiveness of shielding gases in the FCAW process [8]. Some welders believe that using pure CO₂ is more advantageous due to its ability to provide deeper penetration and lower operational costs [9]. Meanwhile, theoretically, the use of a mixed shielding gas—comprising 80% CO₂ and 20% Argon—is considered superior for producing a more stable arc [10], reducing spatter, and resulting in smoother and cleaner welds [11].

Although various studies have discussed the influence of shielding gases on different welding methods and materials, limited research has specifically evaluated the effects of pure CO₂ and mixed gases on the FCAW process applied to AH-36 steel—particularly in the 1G welding position using a Butt Joint with a Single V-Groove and ceramic backing [12][13]. Given the critical role of AH-36 steel in construction and maritime applications, the lack of comprehensive studies that simultaneously assess weld defects, material hardness, and penetration depth highlights the need for further investigation [14].

This study is designed to thoroughly examine and analyze the effects of shielding gas type on the quality of FCAW welds on AH-36 steel [15]. Three key aspects are evaluated: the types of defects observed in the weld [16], the hardness values in the different metal zones (weld metal, heat-affected zone, and base metal) [17], and the weld penetration depth [18].

Therefore, this research aims to evaluate the influence of shielding gas type on the FCAW welding quality of AH-36 steel. The findings of this study are expected to provide both practical and scientific recommendations for the industry in selecting the optimal shielding gas, particularly in terms of mechanical and metallurgical aspects of the weld.

# Methodology

The primary objective of this study is to evaluate the effect of two types of shielding gases—pure CO₂ and MIX gas (80% CO₂ and 20% Argon)—on weld quality in terms of surface defects, hardness, and penetration. This research employed an experimental method, and data collection was conducted in a shipbuilding industry setting.

The equipment used in this study included shielding gas cylinders, an FCAW OTC welding machine (XD-500), a Micro-Vickers hardness tester, and an optical comparator. The research began with a literature review and field study, followed by equipment and material preparation. The welding specimens consisted of AH-36 steel plates with dimensions 400 mm × 200 mm × 10 mm, and the electrode used was AWS A5.20 E71T-1C. Additional materials included surface cleaner/remover, red dye penetrant for visual identification, developer spray, sandpaper, etching solution (a mixture of HNO₃ and alcohol), and clear spray paint (Pilox Clear).

During the welding process, the AH-36 specimens were prepared using a Butt Joint Single V-Groove configuration with a groove angle of 20°, ceramic backing, and filler wire E71T-1C. The non-destructive testing (NDT) was conducted using the dye penetrant method, which included surface cleaning, application of red penetrant, surface cleaning after dwell time, developer application, indication evaluation, and final cleaning.

Hardness testing was carried out using the Micro-Vickers method at three regions: base metal, weld metal, and heat-affected zone (HAZ), with three measurement points per region. Macrographic analysis was performed to evaluate weld penetration for each shielding gas type by applying an etching solution (a mixture of HNO₃ and alcohol) to reveal the weld cross-section.

A descriptive analysis approach was used to interpret the differences between pure CO₂ and MIX shielding gases in terms of surface defects, hardness, and penetration. All collected data were quantified using Microsoft Excel, analyzed through numerical calculations, and presented in the form of bar charts.

# Results and discussion

## Penetrant Testing

**Figure 1.** Effect of pure CO₂ and MIX shielding gas on weld surface defects

The experimental results demonstrate distinct differences in weld quality between pure CO₂ and CO₂-Argon mixture (MIX) shielding gases across three critical parameters: surface defects, hardness distribution, and penetration depth. Figure 1 compares the penetrant test results for both gases, revealing no surface defects exceeding the ASME Section VIII Division I acceptance threshold of 1.5 mm. This suggests that both gases provide adequate shielding to prevent surface discontinuities under controlled welding conditions. However, prior studies indicate that environmental factors (e.g., humidity, surface cleanliness) may influence defect formation, as pure CO₂ has been associated with undercut defects in SS400 steel, while MIX gas tends to produce spatter. The absence of such defects in this study implies optimized welding parameters or environmental controls.

**Figure 2.** Effect of pure CO₂ and MIX shielding gas on Base Metal hardness.

**Figure 3.** Effect of pure CO₂ and MIX shielding gas on Weld Metal hardness.

Microhardness analysis (Figs. 2–4) highlights the superior mechanical performance of MIX gas. In the Base Metal (BM), MIX gas yielded marginally higher hardness (185.42 HVN vs. 180.15 HVN for CO₂), attributed to reduced oxidation and thermal distortion (Fig. 2). The Weld Metal (WM) exhibited the most pronounced difference, with MIX gas achieving 243.62 HVN compared to 165.11 HVN for pure CO₂ (Fig. 3). This disparity stems from the higher heat input of pure CO₂, which promotes grain coarsening and softening. Similarly, the Heat-Affected Zone (HAZ) hardness with MIX gas (223.28 HVN) surpassed that of pure CO₂ (167.29 HVN) (Fig. 4), corroborating previous findings in the literature, which reported elevated hardness in FCAW welds due to improved shielding gas efficacy. The consistent hardness advantage of MIX gas underscores its role in minimizing thermal degradation and preserving microstructural integrity.

**Figure 4.** Effect of pure CO₂ and MIX shielding gas on HAZ hardness.

**Figure 5.** Effect of pure CO₂ and MIX shielding gas on weld penetration depth.

Macro-metallographic examination (Fig. 5) further supports the benefits of MIX gas, showing deeper penetration (2.997 mm) than pure CO₂ (2.944 mm), though both meet the ASME Section IX minimum requirement (20% of plate thickness). The deeper penetration with MIX gas aligns with its enhanced arc stability, which reduces spatter and improves energy transfer to the weld pool. Notably, neither gas produced macro-level defects (e.g., cracks, porosity), satisfying relevant industrial standards. The marginally superior penetration of MIX gas, while statistically slight, may translate to improved joint strength in critical applications, such as offshore structures subjected to cyclic loading.

The combined results underscore a trade-off between cost and performance. Pure CO₂, though economically favorable, exhibits limitations in hardness and penetration due to its higher thermal input and oxidative potential. In contrast, MIX gas mitigates these issues through argon’s inert properties, which stabilize the arc and reduce heat-affected zone degradation. Industrial adoption of MIX gas should consider these mechanical advantages against its higher cost, particularly for applications demanding high fatigue resistance or cryogenic toughness. Future studies could explore intermediate gas mixtures (e.g., 90% CO₂ + 10% Argon) to optimize cost-performance ratios or evaluate these findings under varying environmental conditions (e.g., high humidity, wind exposure).

# CONCLUSION

This study has shown that the type of shielding gas used in Flux Cored Arc Welding (FCAW) significantly influences the weld quality of AH-36 steel. The use of pure CO₂ shielding gas resulted in no detectable surface defects, as confirmed by dye penetrant testing. However, it produced lower hardness values in the weld metal and heat-affected zone (HAZ), which can be attributed to the higher heat input associated with pure CO₂. In addition, macrostructural observations revealed shallower weld penetration, with a depth of 2.944 mm. In contrast, the use of a mixed shielding gas (80% CO₂ and 20% Argon) also showed no visible surface defects, but yielded higher hardness values, particularly in the HAZ, indicating better thermal control and reduced oxidation during welding. The mixed gas also produced slightly deeper weld penetration, reaching 2.997 mm. These findings suggest that the MIX shielding gas offers improved mechanical and metallurgical performance compared to pure CO₂, making it a more suitable option for high-integrity welding applications involving AH-36 steel.

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