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EFFECT OF PURITY LEVEL OF CO_2 SHIELDING ON METAL ACTIVE GAS WELDED JOINT QUALITY

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The investigation deals with the study of the effect of the purity level of carbon dioxide shielding gas on the metal active gas weld quality. Studied 99.78 %, 99.95 %, and 99.97 % purity levels of carbon dioxide shielding gas. Factors considered were related to shielding gas purity, moisture, Sulphur, and oxygen content. Welded samples were subjected to ultrasonic testing to assess weld quality. With the reduction in purity level below 99.9 %, it was observed that the weld defect percentage increased in both lab trials and mass manufacturing jobs. The defects recorded were 5% higher when jobs were welded using carbon dioxide supplied from a gas cylinder than that supplied from liquid cryogenic bullets; this established that a higher purity level could be maintained in cryogenic storage and transport of shielding gases. This states helpful references to manufacturing industries for selecting the purity level of shielding gas, with the objective of rework reduction.

Keywords: Carbon Dioxide; Metal Active Gas (MAG Welding); Ultrasonic Testing; Gas Purity Level; Porosity.

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1. INTRODUCTION

MAG (Metal Active Gas) welding belongs to a family of Gas Metal Arc Welding (GMAW) and is particularly advantageous for its high welding speeds (Pires *et al.*, 2006). It can be operated manually or using a mechanized or robotic setup, based on the requirement. In metal active gas welding, a filler metal or welding wire generates the arc when it touches the component, and consumable wire is used as an allowance to the joint.

To protect the welding arc from the reactive oxygen in the surroundings, a "shielding gas" flows through the gas nozzle and protects the pool (Mvola *et al.*, 2017). This keeps the oxygen away from the pool during welding and therefore prevents oxidation of the molten pool. MAG welding uses active gases such as pure CO_2 or mixed gases (argon, CO_2, O_2) in various compositions as protective shielding gas. The purity level of shielding gas is one of the significant factors for controlling the weld quality and avoiding defects like porosity and lack of fusion to some extent (Nakamura *et al.*, 2008). Kikani *et al.* (2017) also explain the effect of impurities content in the shielding on weld quality. Gülenc *et al.* (2005) Examined impact tests and showed that the toughness of the welding increased with an increase in the amount of hydrogen in argon. For all the welding parameters, the base metal exhibited a higher hardness value than the hardness exhibited by the heat-affected zone (HAZ) and the weld metal. Gadallah *et al.* (2012) Investigated the effects of shielding gas compositions on arc stability, weld penetration, deposition rate, microstructural characteristics, and hardness distribution in the case of plain carbon steel ST 37-3. And reported that the shielding gas compositions significantly affected the arc stability, deposition rate, microstructure, and chemical and mechanical properties of carbon steel welded joints. Among the investigated shielding gas compositions, the shielding gas composed of 75% Ar – 25% CO_2 was the optimum economic shielding gas composition due to its high arc efficiency and deposition rate. Using that shielding gas composition, the microstructure was found to be homogenous due to the balance of the cooling rate.

Boiko *et al.* (2013) reported that the weld penetration, yield strength, tensile strength, and cost of the welding joint were influenced by CO_2 and O_2 content in the shielding gas. Better results were obtained using argon with CO_2 and or O_2 gas mixtures. Acar *et al.* (2020) studied the effect of shielding gas combination on the microstructure, and mechanical properties of MIG welded stainless steel 316. The effect of shielding gases on angular distortion and bead profile parameters of MIG (Metal Inert Gas) welded stainless steel 409L plates was established by (Kashish *et al.*, 2022). Yongan *et al.* (2022) stated the effects of shielding gases on 9% Ni steel hybrid laser arc welding, providing a theoretical basis for LNG storage efficient and reliable manufacturing. Based on the tensile test that has been done. Nur *et al.* (2021) explained the variation of UHP (ultra-high purity) argon gas with a 20 liter/minute flow rate had the best result with a yield strength of 217,32 MPa and

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ultimate strength of 295,83 MPa. The result of the micro photos showed that the GMAW (gas metal arc welding) method produced small dots where the dots were Mg2Si formation, which the more significant number of smaller size dots produced would increase the mechanical properties of the material. One-way ANOVA analysis was conducted by (Rahman *et al*., 2022) to ascertain the statistical difference in hardness among the samples at a 95% confidence level. The results indicated that the argon flow rate significantly positively impacts the hardness of the weld zones as the shielding gas flow rate increases from 0 to 45 SCFH. However, the hardness significantly dropped at 65 SCFH. The drop in hardness was attributed to an increase in the presence of porosity.

Esin *et al.* (2021) investigated the effect of protective gas composition on welding quality in MAG welding by tensile test and observed that the tensile StrengthStrength decreased as the amount of CO_2 increased. At the same time, the O_2 was constant in the shielding gas, or as the amount of O_2 increased while the CO_2 was constant. Mariappan *et al.* (2021) Investigated the effect of alternating shielding gases in gas metal arc welding of SA515 Gr 70 carbon steel and observed that the weld pool dynamics got refined by the enhanced thermos-physical properties driven by the alternating shielding gases. Gejendhiran *et al.* (2019) Investigated process parameters optimization for improving the mechanical properties of IS2062 mild steel weldments by GMAW and observed superior hardness value obtained by Pure (100%) CO_2 with respect to other shielding gas mixtures. The evaluated values tell that the welding current & shielding gas and have an impressive effect on the IS2062 weldment mechanical properties.

Bruno *et al.* (2022) studied the effect of inert and active shielding gases in the corrosion resistance of IN625 weld overlays where cyclic potential-dynamic polarization experiments showed that adding Inconel 625 can enhance the corrosion resistance of low carbon steel to values close to the Inconel 625 alloy itself, for two and three layers deposited. Roy *et al.* (2021) The use of argon 3% nitrogen as a shielding gas mixture for processing 410 steel for tool applications is recommended based on the relatively low cost of this gas mixture and the resulting higher hardness, higher dimensional stability, and lower porosity. MIG welding can be used successfully to join SS304. The processed joints exhibited better mechanical and metallurgical characteristics (Banka *et al.*, 2019). To study the effect of variation in robotic tandem parameters on fatigue properties of welded joints, the following parameters were investigated, viz. first case root & the second pass using a single wire, subsequent run tandem twin and second case using root pass using a single wire, subsequent run using tandem twin wire welding (Sawrav *et al*., 2022).

The influence of shielding gas on the welding process of laser-arc hybrid welding (LAHW) and metal inert gas welding (MIG) was investigated by computational fluid dynamics analysis (CFD) and high-speed photography. The results show that the process stability of MIG under high gas flow rate is poorer than that of LAHW(Yang *et al.*, 2019).

Ar-He is a shielding gas mixture that was used to improve the weld quality of fibre laser-metal inert gas (MIG) hybrid welded aluminum alloy (Chuang *et al.*, 2019).

1.1 Gaps in the literature survey

Considering the available literature and research resources, it was evident that the most versatile GMAW (Gas metal arc welding) process and its sub-type MIG/MAG (Metal inert/active gas welding) process are widely used in welding job manufacturing industries. The welding process control plays a significant role in maintaining the quality of weld joints or avoiding weld defects. It was also evident that the shielding gas is essential in protecting the weld pool from oxidation and environmental impurities to keep the welded joints defect-free. Carbon dioxide is the most used shielding gas, and its purity level is vital in controlling joints' mechanical properties. The available literature also reflects the effect of mixed shielding gases on GMAW or hybrid-GMAW (gas metal arc welding) processes, applicable for various grades of ferrous/non-ferrous metals and steel alloys. To some extent, shielding affects weld penetration and process control, and it also studied the cost.

Overall, the available literature has not focused on the effect of minor changes in the purity level of shielding carbon dioxide from 99.78 % to 99.95 % to 99.97 % purity on weld quality. And its effect on the extent of defect reduction as we increase the purity level of shielding gas. Shielding gas contributes to the purity of weld joints, but the purity of shielding gas has yet to be assessed to a suitable extent. This potential gap for industries has scope for study and can be addressed as a novel work. So, in this work, the effect of minor changes in the purity level of shielding carbon dioxide on weld quality has been investigated. The effect of supply conditions, i.e., the form of carbon dioxide viz. gaseous cylinder or liquid cryogenic bullet supply, was also investigated on mass manufacturing actual jobs. This investigation also strictly follows the guidelines of welding skill qualification and parameters selection for manual sample welding or robotic welding based on pre-qualified WPS (welding process specification), followed as standard practice in the good manufacturing industry, which is as per guidelines of ASME (American society of mechanical engineers). All the purity grades of carbon dioxide selected for sample trial and mass manufacturing jobs were readily available in the market. They could be easily referred to and adopted by industries. Hence it is focused on the specific problem of actual welding manufacturing industries and is relevant for them to consider defect reduction. All the processes and standards followed for welding, testing, and non-destructive examination in this work were commonly followed practice in industries, hence would be easily understandable by industries and can be accepted without significant changes in their existing operations.

Based on the above literature survey and the gaps identified, the following objectives were defined and explained:

a. To study the effect of change in purity level of carbon dioxide shielding gas on metal active gas welding process
b. To study the effect of the form, i.e., gas or liquid carbon dioxide supply, on weld quality
c. Validation of lab trials on actual mass manufacturing structural welded jobs directly relevant to welding industries.

To keep the focus on welding industries, parameters and practices adopted specifically to them for study so that industries can easily refer to it without changing their present setup.

Two purity levels, 99.78 % & 99.95 % of carbon dioxide shielding gas, were selected considering commercial availability for the welding industry. Local industries were surveyed to decide on these two grades. Since the effect of a higher purity level of carbon dioxide on mass manufacturing was an objective, a further survey was done to find the next higher purity grade of industrial carbon dioxide available in the market for weld shielding. Noticed that 99.95% is the best available purity grade for the welding industry. In the further survey, 99.97 % purity grade was available as edible grade/food grade used in beverage industries. Since 99.97 % pure food grade carbon dioxide in the welding industry was never tried out, it has opted for trial as a good alternative.

Hence, selected three purity levels (99.78 %, 99.95 %, and 99.97 %) of carbon dioxide shielding gas. Lab trials were conducted using the three purity levels of carbon dioxide shielding to study the arc's behavior and the weld joints' quality.

In the lab trial, a qualified welder performed the welding under controlled conditions. A study was also conducted on mass-manufacturing products of large-scale industries. In the industry-level experiments, CO_2 was supplied through gas cylinders or the liquid bullet. Also studied was the effect of different supply conditions of CO_2 on weld quality. To understand the microstructural changes of the welded joints through investigation of cross-sectional microhardness welded joints, made samples with different purity grades of carbon dioxide shielding.

Since this investigation was a destructive test and cannot be done on mass manufacturing jobs, it studied the effect of purity of shielding gas on samples made with similar welding parameters with which welded actual mass manufacturing jobs. Since this study was intended to give confidence to the actual mass manufacturing welding industry, where rework control is an essential factor for cost, quality and delivery, so actual jobs were also welded with a selected purity level of gas and assessed the defects through ultrasonic testing, a non-destructive mode of weld examination.

2. MATERIALS AND METHODS

The methodology adopted was first to do an initial industrial survey about the commercially available types and purity of shielding gases. Then to understand the industry problem and the requirement. Further lab and actual mass-manufacturing trials were done with the proposed solutions. Identified the proposed solutions and did suggest trials to get a novel solution for the industry. After conducting a detailed literature survey, gaps were identified, and the methodology adopted is stated in below Figure 1.

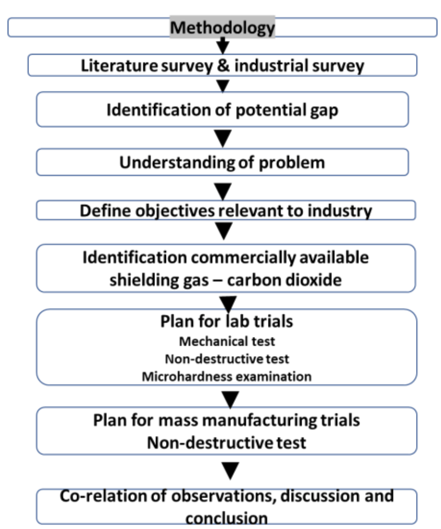

Figure 1. The methodology adopted for research

2.1 Selection of base materials

A standard grade of mild steel, i.e., IS 2062B, was selected as a base material (Indian Standard for Hot Rolled Medium and High Tensile Structural Steel – Specification, 2011). This mild steel grade's chemical composition and mechanical properties are reported in IS: 2062B, as mentioned in Tables 1 and 2, respectively. Odebiyi *et al.* (2019) recommended this grade of steel plate with a carbon equivalent of 0.4 to 0.42 being normalized without any additional requirement of preheating and post-heating to support the strength and quality of weld joints. Das *et al.* (2021) recommended repair welding can return a part to its normal service life if weld failure happens due to service deterioration or defects during the fabrication stage. However, repetitive heat input due to repair welding will cause changes in welded structure and properties.

Table 1. Chemical composition of base material (IS 2062B)

%C Max.	%Si Max.	%Mn Max.	%S Max.	%P Max.	Carbon equivalent
0.23	0.4	1.5	0.045	0.045	0.42

Table 2. Mechanical properties of base material (IS 2062B)

Y.S (Mpa.) Min.	UTS (Mpa.) Min.	% Elongation Min.	Hardness (BHN)	Heat Treatment
250	410	23	120-140	Normalized

Note: UTS: Ultimate tensile StrengthStrength, Y.S: Yield strength, BHN: Brinell hardness number, Mpa: Mega pascals

Preheating was done at a temperature of 100 ° C to remove moisture from the surface of the weld sample. The butt joints were made on the samples for the lab trial, as shown in Figure 2. The thickness of the plate used was 25 mm.

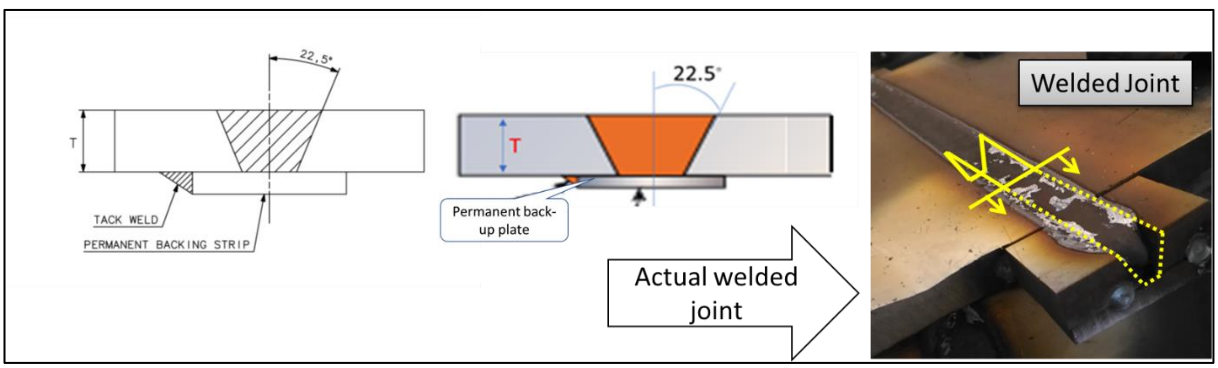

Figure 2. Type of weld joint (Butt configuration T: the thickness of the plate)

Das *et al.* (2021) also stated that fabricated structural components of heavy machinery are one of the mass manufacturing welding industries. Heavy earth-moving machinery is used for mining and construction work. Fabricated structural components are made of different thicknesses of mild steel IS 2062-B plates and primarily have two straight butt joints and four circular butt joints. Studied ultrasonic test data of those six butt joints for thirty jobs.

2.2 Selection of weld consumables:

The welding wire ER70S-G was used to fulfill the ASME requirement (American society of mechanical engineers- Section II C. SFA 5.18, 2005), for which chemical composition and mechanical properties are described in Table 3 and Table 4.

Table 3. Chemical composition of ER70S-G welding wire

Element	Specified % content
%C	0.06-0.15
%Si	0.80-1.15
%Mn	1.40-1.85
%P	0.025 max
%S	0.035 max
%Cu	0.50 max
%Ni+%Cr+%V+%Mo	0.50 max

Table 4. Mechanical properties of ER70S-G welding wire

Properties desired	Specified value
Ultimate tensile StrengthStrength	490 Mpa min
Yield strength	400 Mpa min
% Elongation	22 % min
Impact Strength	27 J min at -30˚C

2.3 Selection of carbon dioxide shielding gas

Selected three purity levels (99.78 %, 99.95 %, and 99.97 %) of carbon dioxide shielding gas for conducting the experiments in lab trials. For welding of mass manufacturing, actual jobs 99.1% purity level of carbon dioxide supplied through the gas cylinder and a 99.5 % purity level of carbon dioxide supplied through a liquid bullet were used.

2.4 Welding parameters

Lab trials were done by manual welding of butt joint samples. To have better control of the welding process, qualified welders were employed. Welder qualification was done according to the guidelines of ASME (American society of mechanical engineers) BPVC (boiler pressure vessel code) Section IX. Article III of Section IX (2019). A good quality welding output can only be desired if selected input materials, input consumables, and machine conditions are good, in addition to the technology of the welding process adopted and the skill of the welders doing the job or welding. So, welders' skill was assessed per guidelines of (the American society of mechanical engineers) BPVC (boiler pressure vessel code) Section IX. Article III. (2019) Welders assessed and qualified per this guideline were considered to have better process control, parameter control and desired skill to work within specified welding parameters. To avoid or eliminate the variation in welding parameters and skill issues, qualified welders before making the welding samples. A qualified welding procedure specification (WPS) has been referred for the selection of welding parameters, which is established as per guidelines of ASME (American society of mechanical engineers) - Section IX, Part QW, Article II (2015).

For lab trials, a digital arc, 3-phase welding machine with a rated input voltage of 08 ± 10% (50 / 60 Hz) and rated input power of 8.2 kVA at 60 % duty cycle was used. This welding machine provided a rated output voltage of 36 V and a rated output current of 350 A. The current and voltage ratings meet the requirement of our WPS (welding procedure specification) and are specified in Table 5A.

A robotic welding setup used for welding heavy structural jobs. The welding robot was equipped with a six-axis welding manipulator with a trans-pulse synergized 5000 weld power sources, an automatic wire feed gas nozzle, and an arc seam tracking system for MIG/MAG. This welding robot has a power supply of 3 x 400 V, a continuous current feed of 180 to 300 A, a 100 % duty cycle, and a power rating of 13.1 kVA.

The current and voltage ratings meet the requirement of our WPS (welding procedure specification) and are specified in Table 5B. Deployed these parameters for robotic welding of actual mass manufacturing structural jobs. The parameters mentioned in WPS (welding procedure specification) were the standard parameters adopted for similar types of welding components. The range of parameters mentioned in WPS (welding procedure specification) was derived from the best suitable range of parameters from various experimental samples, giving the best mechanical and metallurgical results. And, if it is advised to follow the suggested parameters of WPS, ensure desired mechanical and metallurgical properties of welded joints. So, in this work, a pre-qualified WPS (welding procedure specification) parameter range was selected for welding to avoid or eliminate the effect of improper welding parameters on mechanical & metallurgical tests and addressed only the effect specific to the purity level of shielding gas.

Table 5A. Range of welding parameters used for lab trial sample welding

Sl. No.	Welding Parameter		Value
1	Voltage in Volts	Root run	28-32
		2nd pass	28-33
		3rd pass	30-35
		4th pass	30-35
2	Current in Amps	Root	280-300
		2nd pass	290-310
		3rd pass	320-340
		4th pass	323-340
3	Weld length in mm	Sample length	300
4	The gas flow rate in lpm	Supply gas	20
5	Polarity	Fixed -DCEP	DECP
6	Job to nozzle tip distance in mm	Fixed- 15 mm	15

Table 5B. Parameters of welding done.

Plate thickness of structural component welded in mm	Plate grade	Weld pass no.	Current in Amperes	Voltage in volts	Job to nozzle tip distance in mm	The gas flow rate in LPM (liters per minute)
16	Mild steel, IS2062-410 B	Root run	270-275	25-26	15	18-20
		2nd pass	277-280	26-27	15	18-22
		3rd pass	260-264	25-26	15	18-22

2.5 Investigation of weld samples using ultrasonic testing

As per (Dwivedi *et al.,* 2017), ultrasonic testing involves using ultrasonic sound waves to detect defects inside a material. (Baughurst *et al.*, 2011) stated that welded joints may have defects inside the welds or sometime near the weld zone. The few defects often found in welds are porosity, crack, slag inclusion, lack of fusion, penetration, root concavity, etc. As per recommendations of Written Practice for NDE Personnel Qualification and Certification LANL Engineering Standards Manual STD-342-100 (2019), since these defects lie inside the weld, ultrasonic scanning is utilized to detect these discontinuities. An ultrasonic testing machine with a probe specification of 22.5°, 70 MHz was used to investigate lab trial samples and mass manufacturing welded jobs. The ultrasonic testing inspectors were qualified as per guidelines of ASNT-SNT-TC-1A (American Society for Nondestructive Testing), Level II as stated in Written Practice for NDE Personnel Qualification and Certification LANL Engineering Standards Manual STD-342-100 (2019). To understand the defect nature, a phased array of ultrasonic testing has been deployed on defective joints to find the defect map. The identified defects are subjected to gouging to remove defects. Carbon arc-air gouging is a standard technology for repairing defects in welded structures. The skill of weld gouging operators is equally important, as the skill of welders involved in welding and weld rectification is essential. The skill of gouging operators is considered necessary, considering their capability to identify defects during gouging and optimized gouging to avoid joint damage (Sawrav *et al*., 2022).

2.6 Mechanical tests of weld samples

All weld mechanical test specimens were drawn from the welded lab trial samples, and the sample was welded for testing welding wire as consumable. Chemical analysis tests were conducted using a spectrometer instrument. Tensile testing samples were cut from the all-weld joint test specimen, as shown in Figure 3. The test was conducted as per ASTM (American Society for Testing and Materials)- E8/E8M − 16a, Standard Test Methods for Tension Testing of Metallic Materials (2016). A unidirectional gradual tensile load was applied on 60 Ton universal testing machine on a round bar sample.

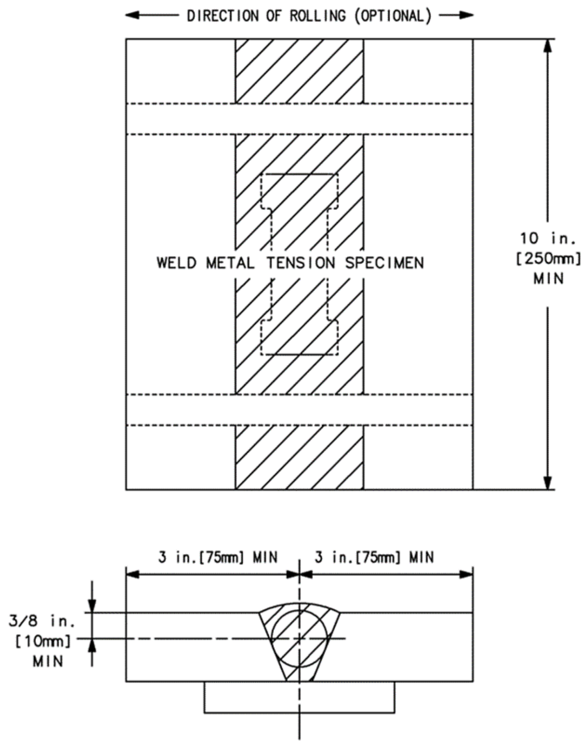

Figure 3. Orientation of tensile test specimen

Impact tests were conducted as per guidelines of IS 1757 (1988): Method for Charpy impact test (V notch) for metallic material. A Charpy impact sample was prepared with a 45° V notch having a depth of 2 mm and a 0.25 mm radius. The impact test was conducted at -30° C. Mechanical test specimens were made as per details shown in Figure 3 and Figure 4.

Microhardness of the weld sample across the weld section was measured as per guidelines of ASTM (American Society for Testing and Materials) E92 – 17, Standard Test Methods for Vickers Hardness and Knoop Hardness of Metallic Materials (2017). A diamond indenter was used for measuring microhardness, and a load of 500 gm with 10 seconds of dwell time was applied.

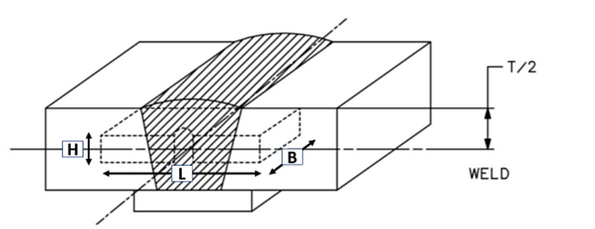

Figure 4. Orientation of impact test specimen from weld sample at the center of the thickness of the plate (L=50 mm, B=H-10 mm)

2.7 Lab trials

In the lab trial, three grades of carbon dioxide, 99.78 %, 99.95 %, and 99.97 % purity level, were used for MAG welding. After ultrasonic testing of the lab trial samples, once the samples were free of defects, the samples were subjected to the physical and chemical composition of CO_2 for each purity level and were evaluated as per IS-307– Specification for Carbon–dioxide (1996). Welding of samples was done as per the parameters specified in Table 7.

DECP (Direct current electrode positive) polarity was used for welding, with the job to nozzle tip distance of 15 mm. Three samples were welded for each grade of carbon dioxide. The parameters used were within the range specified in referred qualified WPS (welding procedure specification), which was established as per guidelines of ASME (American society of mechanical engineers)-Section IX, Part QW, Article II (2019).

2.8 Mass manufacturing job details:

In this case, the fabricated structural components of heavy machinery were selected for welding. The atmospheric parameters such as dew point temperature, relative humidity, ambient air temperature, and job surface temperature were monitored using an infrared thermometer and hygrometer.

The atmospheric parameter range in which welding was done is described in Table 6. For welding, MAG robotic setup was used. The setup runs on a fixed range of electrical parameters, as listed in Table 7, and observations were for the actual range of parameters adopted during welding against specifications of WPS (welding procedure specification), as mentioned in Table 5B.

Table 6. Range of atmospheric parameters for doing shop trials

% Relative humidity	Average ambient air temperature (deg. C)	Average dew point in deg. C
50 - 55	19-20	11.3-12.1
52 - 55	20-21	12.4-13.7
53 - 57	20-23	12.9-13.7

Table 7. The actual range of parameters of welding done

Plate thickness of structural component welded in mm	Plate grade	Weld pass no.	Current in Amperes	Voltage in volts	Job to nozzle tip distance in mm	The gas flow rate in LPM
16	Mild steel, IS2062-410 B	Root run	270-275	25-26	15	18-20
		2^{nd}pass	277-280	26-27	15	18-22
		3^{rd} pass	260-264	25-26	15	18-22

3. OBSERVATION

3.1 Observation of lab trial samples

The composition for selected purity grades of carbon dioxide is listed in Table 8. The test revealed the presence of impurities such as moisture and oxygen in the CO_2 gas. Owing to the high purity level of carbon dioxide, traces of other impurities, such as oil & Sulphur, were found. Although moisture content was in the range of 2-3 ppm, the welding quality might get affected. Sample gases were found to be tasteless and odorless.

Table 9 describes the weld sample test report, such as arc stability, weld defects, spatters, etc., for each purity level of CO_2. As stated by the welder, arc stability was found to be better in the case of 99.95 % and 99.97 % carbon dioxide shielding gas than with 99.78 % carbon dioxide gas. The samples were evaluated for ultrasonic testing to check the weld quality. Porosity and slag inclusions were observed for the samples welded with 99.78 % purity carbon dioxide shielding gas. However, for the other two grades of shielding gas, no such defects were noticed via ultrasonic testing. Porosity in sample 2 welded with 99.78 % purity shielding gas was attributed to the higher moisture content in the gas, i.e., 3.1 ppm. Other factors like improper inter-pass cleaning might have caused slag inclusion in the 3rd sample.

Sidewall fusion was not detected in any of the samples. Also, the samples welded with 99.78 % purity shielding resulted in higher fumes and surface spatters than the other two grades of shielding gas. Thus, the purity level of carbon dioxide shielding gas significantly impacts the weld quality, generation of fumes and spatter, etc. As the purity level of shielding gas was increased, the arc stability was improved with lower defects inside the weld and reduced spatters on the surface.

Table 8. Composition for selected purity grades of Carbon dioxide

Sl. No.	Properties	Observed properties		
1	Purity	99.78 %	99.95 %	99.97 %
2	Moisture	3.1 ppm	2.6 ppm	2.5 ppm
3	Odor	Odorless	Odorless	Odorless

Sl. No.	Properties	Observed properties		
4	Taste	Tasteless	Tasteless	Tasteless
5	Traces of oil	Not traceable, <0.1 ppm	Not traceable, <0.1 ppm	Not traceable, <0.1 ppm
6	Sulfur content	Not traceable, <0.1 ppm	Not traceable, <0.1 ppm	Not traceable, <0.1 ppm
7	Oxygen concentration	80 ppm	40 ppm	30 ppm
Note: ppm= parts per millions				

Table 9. Weld sample test report for selected purity grades of carbon dioxide

Sl. No.	Content analyzed	Carbon dioxide purity level		
1	Purity	99.78 %	99.95 %	99.97 %
2	Arc stability (welder's comment)	Good	Very good	Very good
3	Ultrasonic test straight past observations	1st Sample: No defect 2nd sample: pin holes (Affected 5 mm sq. area) 3rd Sample: Slag inclusion (Affected 5 mm sq. area)	1st Sample: No defect 2nd Sample: No defect 3rd Sample: No defect	1st Sample: No defect 2nd Sample: No defect 3rd Sample: No defect
4	Sidewall fusion	Good- no defect	Good- no defect	Good- no defect
5	Spatters over weld	High	Few	Few
6	Other remarks	High fumes	Medium fumes	Medium fumes & wide weld bead

The chemical composition and mechanical properties of lab trial samples welded with three different grades of carbon dioxide were recorded in Tables 10 and 11, respectively.

Table 10. Chemical composition of samples welded

Specification	For the sample welded with 99.78 % purity Carbon dioxide	For the sample welded with 99.95 % purity Carbon dioxide	For the sample welded with 99.97 % purity Carbon dioxide	Observations for all weld test specimens to verify ER70S-G welding wire
%C - 0.06-0.15	0.076	0.08	0.067	0.089
%Si - 0.80-1.15	0.90	1.0	0.97	0.91
%Mn - 1.40-1.85	1.56	1.44	1.51	1.55
%P - 0.025 max	0.007	0.01	0.01	0.014
%S - 0.035 max	0.005	0.009	0.008	0.022
%Cu- 0.50 max	0.201	0.37	0.41	0.21
%Ni+%Cr+%V+%Mo-0.50 max	0.069	0.054	0.053	0.049

Table 11. Mechanical properties of samples welded

Specification	Observations for sample welded with 99.78 % purity Carbon dioxide	Observations for sample welded with 99.95 % purity Carbon dioxide	Observations for sample welded with 99.97 % purity Carbon dioxide	Observations for all weld test specimens to verify ER70S-G welding wire
Tensile StrengthStrength - 490 Mpa min	506	516	524	509
Yield Strength- 400 Mpa min	457	467	481	441
%Elongation - 22 min	28	29	31	28
Impact Strength 27 J min at -30˚C	Avg. 230 J	Avg. 218 J	206 J	Avg. 233 J

Note: UTS: Ultimate tensile StrengthStrength, Y.S: Yield strength, BHN: Brinell hardness number, Mpa: Mega pascals, J: joules

The microhardness measurement was taken, starting from the base metal (section A) to the heat-affected zone (HAZ) section (B) and then towards the weld metal or joint (section C). The microhardness for the samples welded with 99.78%, 99.95%, and 99.97% purity levels of carbon dioxide shielding gas was compared in Figure 5. It has been observed that the microhardness of base metal obtained in this case is well within the range of microhardness of mild steel grade reported in another paper (Arya. *et al.*, 2014). Table 12 represents the percentage increase in microhardness from base metal to HAZ (heat affected zone), i.e., (A to B) and HAZ (heat affected zone) to weld zone, i.e., (B to C), for all three purity levels of CO_2. The highest percentage increase in hardness was observed for samples welded with 99.97 % carbon dioxide shielding. The microhardness increased by 6.38 % from base metal to HAZ (heat affected zone), i.e., (A to B) and 10.59 % from HAZ (heat affected zone), i.e., to Weld zone (B to C). As per the study, a 10 % increment in microhardness was usually obtained in such cases (Arya. *et al.*, 2014).

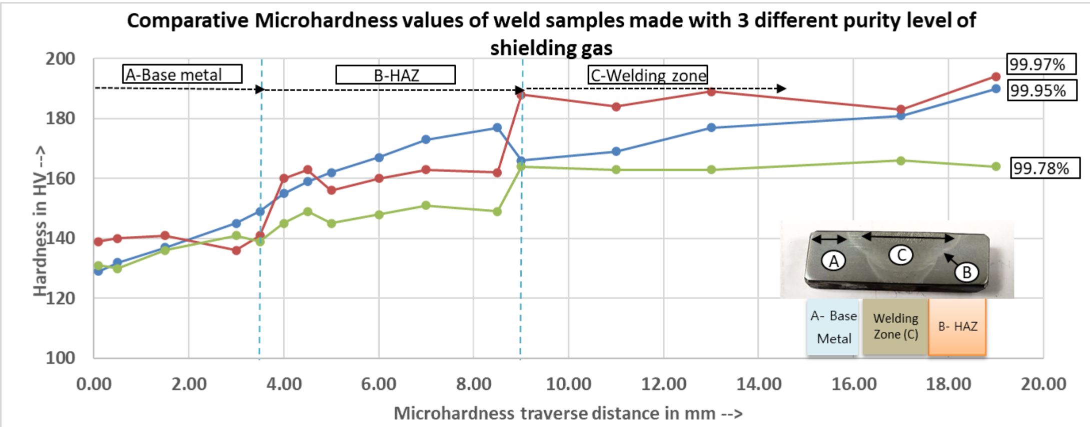

Figure 5. Comparative microhardness for weld samples made with three purity grades of carbon dioxide as shielding gas

Table 12. Percentage increase in microhardness while changing zone

Traverse Zone	99.78% purity shielding	99.95% purity shielding	99.97% purity shielding
Base metal to HAZ (A to B)	4.32%	4.03%	6.38%
HAZ to Weld zone (B to C)	10.07%	4.62%	10.59%

3.2 Mass manufacturing job study observations

The mass manufacturing structural components were welded per parameters stated in Table 5B, with two grades of carbon dioxide shielding, specific to the study effect of supply condition, i.e., 99.1 % purity gas cylinder and 99.5 %-liquid Carbon dioxide supply on weld quality. Did ultrasonic testing on a total of 90 butt joints selected from mass manufacturing jobs for each 99.1 % purity carbon dioxide cylinder supply and 99.5 %-liquid carbon dioxide supply shielding gas.
Study the effect of supply conditions or form of gas in addition to purity levels of shielding gases. Details of the job welded and the results of ultrasonic testing are described in Table 13. When welded, in the jobs with 99.1 % purity carbon dioxide shielding supplied in the cylinder, no defects were found on 81 butt joints, whereas 6.67 % of joints displayed porosity and 3.3 % of joints showed a lack of fusion defect.

However, when liquid carbon dioxide with 99.5 % purity was used for welding, the ultrasonic testing results were found to be improved. No defects were found in 85 joints. Porosity was found in only one joint (1.1 % of joints), and lack of fusion was detected in only four joints (4.4 % of joints).

Thus, from the ultrasonic analysis, a higher purity level of shielding gas supplied as liquid Carbon dioxide resulted in reduced porosity defect in welding. Sample defect maps for porosity and lack of side wall fusion during phase array ultrasonic inspection are shown in Figure 6 and Figure 7, respectively.

Table 13. Details of job welded, and results of ultrasonic observations

Job welded with 99.1%-cylinder gas Carbon dioxide supply.				Defect information
Sl. No.	Job No.	Number of joints tested ultrasonic testing	No. of joints passed in ultrasonic testing	
1	A1	6	5	Pin holes
2	A2	6	6	No defect
3	A3	6	4	Lack of side wall fusion & pin holes
4	A4	6	5	Lack of side wall fusion
5	A5	6	5	Pin holes
6	A6	6	6	No defect
7	A7	6	6	No defect
8	A8	6	6	No defect
9	A9	6	5	Pin holes
10	A10	6	6	No defect
11	A11	6	4	Lack of side wall fusion & pin holes
12	A12	6	6	No defect
13	A13	6	6	No defect
14	A14	6	6	No defect
15	A15	6	5	Pin holes
Job welded with 99.5 %-liquid Carbon dioxide supply.				Defect information
Sl. No.	Job No.	Number of joints tested ultrasonic testing	No. of joints passed in ultrasonic testing	
16	A16	6	6	No defect
17	A17	6	6	No defect
18	A18	6	5	Lack of root fusion
19	A19	6	6	No defect
20	A20	6	6	No defect
21	A21	6	6	No defect
22	A22	6	4	Lack of side wall fusion & pin holes
23	A23	6	5	Slag inclusions
24	A24	6	6	No defect
25	A25	6	6	No defect
26	A26	6	6	No defect
27	A27	6	6	No defect
28	A28	6	6	No defect
29	A29	6	6	No defect
30	A30	6	5	Lack of side wall fusion

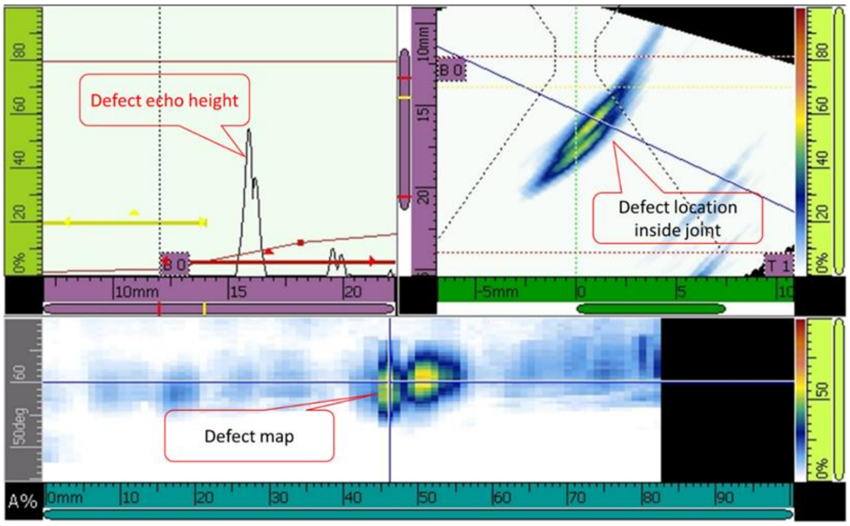

Figure 6. Sample defect map for porosity as indicated in Phase array ultrasonic testing inspection

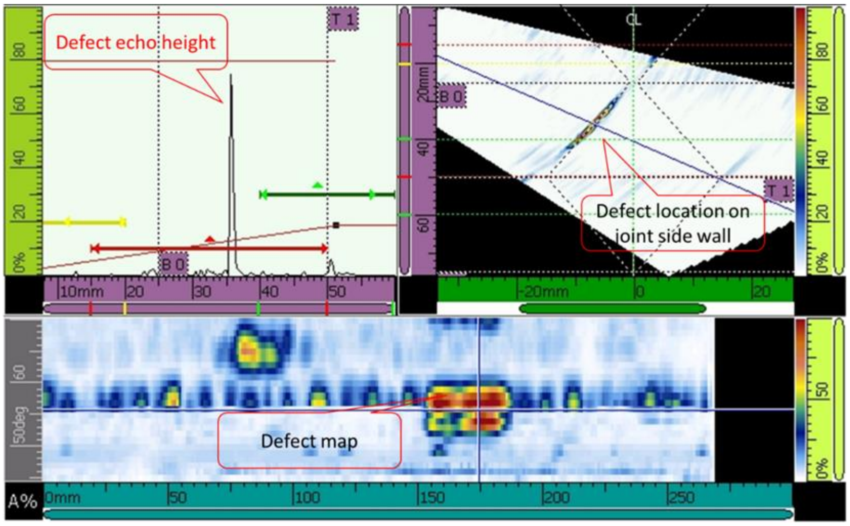

Figure 7. Sample defect map for lack of side wall fusion as indicated in phase array ultrasonic testing inspection

4. CONCLUSION

Three different purity levels (99.78%, 99.95 % & 99.97 %) of CO_2 as a shielding gas were used for MAG (Metal Active Gas) welding of mild steel plates. Two purity levels, 99.78 % & 99.95 % of carbon dioxide shielding gas, were selected considering the most commonly available grade of carbon dioxide for the welding industry. Local industries were surveyed and decided on these two grades. Since investigating the effect of higher purity levels of carbon dioxide on mass manufacturing, a further survey was conducted to determine the next purity of higher grade. Noticed that 99.95% was the best available purity grade for the welding industry. 99.97 % purity grade was available as edible / food grade, used in beverage industries. Since 99.97 % was never tried out in the welding industry, it has opted for trial as a good alternative.

The following conclusions can be drawn from this investigation.

a) All three purity grades of carbon dioxide were evaluated for their composition and physical properties. The presence of moisture & oxygen impurities was revealed. Traces of other impurities, such as oil & Sulphur, were found. Although moisture content was in the range of 2-3 ppm, it significantly affected the welding quality, resulting in porosity defects.
b) The purity level of carbon dioxide used for welding influenced the weld quality, fumes, spatter formation, etc. As the purity level of shielding gas was increased, the arc stability was improved, fewer defects were observed inside the weld, and fewer spatters were found on the surface. Samples welded with 99.78 % purity shielding resulted in higher fumes and surface spatters than the other two grades of shielding gas.
c) The form of gas supply was explored, i.e., the cryogenic liquid form available for edible/food grade for beverage industries in place of gaseous cylinder generally used for welding industries. Apart from lab trials, welding was also done on the fabricated structural components of heavy machinery. For this purpose, two grades of carbon dioxide shielding, i.e., 99.1 % purity carbon dioxide shielding from a gas cylinder and 99.5 % purity carbon dioxide shielding supplied from the liquid source, were used. Ultrasonic testing results indicated that a higher purity level of shielding resulted in a reduced porosity defect in welding.
d) The samples welded with different grades of CO_2 were subjected to mechanical testing. No significant changes in the ultimate tensile strength, yield strength, and impact strength of the welded samples were observed.
e) The microhardness testing of the samples revealed that for all the purity levels of CO_2, there was a gradual increase in hardness from the base metal to the weld zone, and the observed microhardness value is well within the range of mild steel grade observations. The highest percentage increase in hardness was observed for the samples welded with 99.97 % carbon dioxide shielding gas. The microhardness increased by 6.38 % from base metal to HAZ (heat-affected zone) and 10.59 % from HAZ (heat-affected zone) to Weld zone.
f) The CO_2 gas, when supplied through cylinders, may affect the weld quality owing to the less control on cylinder cleaning while re-filling, as compared to direct shielding gas supplied from the liquid source like installed bullets, considering control on purity level.

From this investigation, it can be concluded that a higher purity level of carbon dioxide as shielding gas reduced the porosity defect. However, no substantial improvement in the mechanical properties of the joint was observed. Reducing defects may be cost-effective for manufacturers in terms of rework cost and time. And it is subjected to future study and assessment on a larger sample size.

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