Experience with advanced welding techniques (RMD & P-GMAW) with seamless metal cored wire for Oil & Gas pipeline industries

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Abstract. Regulated Metal Deposition (RMD™) process is a variant of Gas metal arc welding process (GMAW), which was developed with the aim to effectively control the metal transfer in the short-circuiting mode. The process is fundamentally a modified short-circuit GMAW process wherein a uniform droplet deposition, making it easier for the welder to control the puddle and hence achieve an enhanced quality of welded joints. In the present study, RMD technique has been established for API grade pipe (API 5L PSL2 X70 grade) particularly for depositing the root pass on 24" OD and 10.3 mm thick pipe. In addition to this, the RMD technique is tried for the first time with seamless metal cored wires (Megafill 240 M) in order to enhance the deposition rates in Indian Oil & Gas pipeline industry. The joint fill up is further attempted with pulsed GMAW technique using metal cored wires and further analysed. The weldments were tested by mechanical characterization. Mechanical characterization such as tensile properties, impact properties, bend test as well as all weld tensile properties of the weld joint were evaluated and found to be acceptable. A techno-commercial evaluation of the technique was carried out vis-à-vis conventional welding techniques such as SMAW process for root passes and Fill & Cap. It was found the proposed technique was cost effective as well as reliable. One of the inherent benefits of the RMD and Pulse GMAW technique is the reduction in the overall heat input of the welded joint imparting superior mechanical properties. The use of metal cored wires also established the proposed technique as a potential technique for heavy thick weldments by enhancing the overall productivity.

1. Introduction

Steel is an alloy of iron and carbon with varying proportion of additional elements. The properties of steel vary based on its constituents. Depending on the properties of steel, it is used widely in the construction of buildings, tools and machines. Welding is used extensively for joining steels plates or pipes. Large number of welding processes are available to choose from. The selection of welding process is contingent upon various factors like plate thickness, weld metal deposition rate, weld time, equipment cost, heat input etc.

Arc welding processes include Shielded metal arc welding, gas tungsten arc welding, gas metal arc welding, and plasma arc welding. SMAW is the simplest and cheapest of all arc welding processes. However, frequent stops for changing the electrode leads to increased time consumption. The weld strength and ductility obtained in TIG are greater compared to SMAW process [2]. TIG welding also generates less spatter and better weld geometry than SMAW, but the deposition rate is lower [3] compared to SMAW. The penetration obtained in TIG welding with argon gas is restricted to 3 mm,
which can be increased only slightly with the use of helium or hydrogen mixed with argon as a shielding gas. [12-14]. This renders the TIG welding process ineffective for welding plates with a higher thickness in a single pass. Gas welding faces similar issues while welding plates of higher thickness. On the other hand, MIG welding can give penetration depth up to 6.4 mm. [15]. MIG welding also provides higher deposition rates compared to TIG welding. But, MIG welding is a high heat input process which leads to grain coarsening, reducing the impact energy and toughness [4]. Due to high heat input, the angular distortion of welded plates also increases. Apart from the solid wire used in GMAW, tubular cored wires have also been used for welding, coating and hard facing. [5-7]. Depending on the tubular wire filled with flux powder or metal powder, it is called flux cored wire or metal cored wire, and the process is called flux cored arc welding and metal cored arc welding respectively. Use of FC wires over solid wires decreases the spatter rate and increases metal deposition. However, in FCAW, the slag inclusion in the weld pool is higher due to impurities arising from both flux and shielding gas. Due to higher inclusions, it’s ultimate tensile strength and elongation is lesser compared to solid wire [9]. Metal-cored arc weld has very low micro-inclusion content due to absence of flux ingredients. The low micro inclusion content improves the toughness of welds. Hence metal cored arc welding can be considered as an alternative welding process as compared with flux cored arc welding to ensure toughness of welds [8]. Metal cored wires are found to increase the penetration and decrease the spatter. The values of deposition rate of MC wires are also higher compared to FC and solid wires. [10] Due to lower values of heat input, the angular distortion is minimal in case of MCAW [11].

1.1 Steel
Steel with low carbon content (0.05 % to 0.25%) and additional alloying elements has found application in the construction of oil and gas pipelines [1]. API 5L PSL2 X70 grade, especially are suitable for high pressure gas pipeline. Addition of Mn is found to improve tensile and yield strength.

1.2 MCAW
Metal cored wires incorporate the advantages of both solid wires and flux cored wires. The construction of metal cored wires is similar to flux cored wires. The outer metallic coating of metal cored wire conducts the electric current. The current density in metal cored wires is higher compared to solid wires due to decreased current conduction area. Due to higher current density, the deposition rate increases for same current level compared to solid wire.

![Figure 1. Advantages of MCAW vs. GMAW](image)

Deposition efficiency refers to the amount of electrode material that becomes a part of weld metal. Solid wires have very high deposition efficiency as most of the electrode material becomes a part of the weld metal. However, flux cored wires have lesser deposition efficiency (84 – 89%) as the core of the wire contains flux powder, which is deposited on the top of weld metal in form of slag. [18] Metal-cored
wires, with their arc characteristics similar to those of solid GMAW wires, have low spatter formation as well as low slag volume, which exhibit deposition efficiencies in the 92–98% range with the selection of spray transfer mode and shielding gas mixtures with high argon percentage [19]. Metal cored wires have a lower value of heat input compared to solid wires. [19] As a result, the heat affected zone is also smaller, which is shown in figure 2.

| GMAW      | FCAW  | MCAW   |
|------------|-------|--------|
| HAZ width: | 4.72mm| 4.52mm |
|            |       | 4.29mm |

**Figure 2.** Comparison of weld profiles for the GMAW processes

Metal cored wires allow up to 30% increase in travel speed. [18] High deposition rates and efficiency coupled with high travel speed result in increased productivity and a significant reduction in labor costs. Several studies have been conducted on using TIG welding for root pass and subsequent passes by SMAW [20, 22], or followed by FCAW [21]. Some researchers have studied FCAW and GMAW for root and filler passes and vice versa [23].

### 1.3 RMD

Regulated metal deposition (RMD) technique is a modified short-circuiting arc technique introduced by Miller Electric company in 2004. The RMD technique typically is founded on the application of advanced software for modified short circuit transfer GMAW welding that screens the welding current in every step of the short-circuiting phase. The wave profile typically depends on the material composition and thickness to be welded. RMD technique anticipates and controls the short-circuit phase and selectively reduces the welding current in order to create a steady metal transfer. An accurately controlled metal transfer delivers undeviating droplet deposition, which makes it easy for the welder to control the puddle. In order to understand the precise way in which the short circuit is controlled a typical RMD cycle is divided into seven different phases as shown in Figure 3.

**Figure 3.** RMD technique cycle

### 1.4 Pulsed GMAW

In GMAW process, metal transfer can occur by one of the four modes: short circuit, globular, spray, pulsed-spray. In short circuit metal transfer mode, the electrode is in contact with the workpiece and metal transfer occurs as a result of short circuit. As the current value in this method is the lowest, the heat input is also low. But it has been found that spattering occurs at the beginning and end of weld [28a]. Globular metal transfer mode operates at a current value higher than short circuit metal transfer.
In globular mode first big metal droplet is formed at the end of electrode and due to the gravitation force, it deposited over the metal plates. [25] Usually, globular formation is uncontrolled and results in high spattering. With the increase in current value, globular transfer changes into spray transfer. In spray transfer, fine metal droplets are deposited in the weld pool instead of a globule. [29]. Due to smaller size of droplets, the disturbance caused in weld pool is smaller compared to globular transfer, resulting in less spatter. This method significantly improved productivity and reduce manufacturing costs.

A variant of spray metal transfer is pulsed-spray metal transfer or P-GMAW. In P-GMAW, the value of current varies from low-level background current and high-value peak current. The average current value remains less than the threshold value of spray transfer process [30]. At the end of a pulse, a molten metal droplet is formed at the electrode tip. At this time, the current value increases which detaches the droplet from the electrode and depositing it in the weld pool. After the droplet has detached, the current value decreases, resulting in a cooling off period. During cooling period, no metal transfer occurs and weld pool freezes slightly, which helps to prevent burn-through. [31,32,33].

2. Experimental work

2.1 Base material and filler wire

API 5L PSL2 X70 grade was selected for the current study and matching Metal cored wires designated as AWS A5.28: E80C-Ni1 H4 with 1.2 mm diameter was used as filler material. The chemical composition and mechanical properties of the filler wire as well as base metal is as shown in table 1. The as-received pipe of thickness 10.3 mm was machined into size of 300 x 200 mm with using a flame cutting for further trials.

| Table 1. Chemical Composition of the filler wire and base metal |
|-------------------|-------------------|
| **Content**       | **Metal cored wire** | **Base metal** |
|                   | **(E80C-Ni1 H4)**  | **(API 5L PSL2 X70)** |
| Carbon             | 0.053              | 0.12           |
| Manganese          | 1.46               | 1.70           |
| Phosphorous        | 0.008              | 0.025          |
| Sulphur            | 0.005              | 0.015          |
| Silicon            | 0.554              | 0.45           |
| Copper             | 0.11               | 0.002          |
| Nickel             | 0.93               | 0.00           |

| Table 2. Mechanical Properties of the filler wire and base metal |
|-------------------|-------------------|
| **Mechanical property** | **Metal cored wire** | **Base metal** |
| Tensile strength (MPa) | 653               | 625 MPa        |
| Yield strength (MPa)  | 581               | 550 MPa        |
| Elongation           | 26.20 %           | 28.25 %        |

2.2 Welding trials

Miller make XMT 350 FieldPro machine with inbuilt ArcReach technology and Smart feeder for work in remote place like pipeline sites was used for carrying out the RMD as well as pulsed GMAW process as shown in figure 4. The welding was carried out in semi-automatic 5G position by a qualified welder as per ASME section-IX. Different welding process parameters were selected based on this study for root pass as well as subsequent passes by RMD and Pulsed GMAW technique respectively as shown in table 3. Butt welding trials were taken on 24” OD and 10.3 mm (t) pipe having conventional weld edge...
preparation of single V with 60° groove angle. Prior to welding, the pipes were pre-heated to a temperature of 100°C. The root pass was made by RMD process and the consequent filler passes were done by pulsed GMAW process with parameters as shown in table 3. Metal cored wires were used as filler wires both in RMD and GMAW-P process. The interpass temperature was maintained at 250°C. Welding gas mixture of 80 % Ar and 20 % CO2 was used at a flow rate of 18 – 20 liters/minute. The diameter of filler rod was 1.2 mm.

Figure 4. Miller make: XMT 350 FieldPro welding power source

Table 3. Welding parameters for RMD and GMAW-P process

| Weld process | Voltage (V) | Current (A) | Wire feed speed (in/min) | Time (sec) | Travel speed (mm/min) | Heat input (kJ/mm) |
|--------------|-------------|-------------|------------------------|-----------|----------------------|-------------------|
| RMD          | 15 - 16     | 114-126     | 120                    | 337       | 106                  | 1.05              |
| GMAW – P F1  | 20-23       | 130-140     | 180                    | 305       | 118                  | 1.60              |
| GMAW – P F2  | 22 – 23     | 180-195     | 250                    | 270       | 160                  | 1.68              |
| GMAW – P F3  | 22-23       | 180-200     | 260                    | 275       | 165                  | 1.67              |
| GMAW – P C1  | 22-23       | 160-165     | 211                    | 189       | 190                  | 1.18              |
| GMAW – P C2  | 22-23       | 160-165     | 211                    | 189       | 190                  | 1.18              |

2.3 Testing and characterization:
The sample for macro study was taken from the center of the welded plate and subjected to mechanical grinding, polishing (320 grit silicon carbide), followed by etching in a solution of 2% Nital. An optical microscope (Travelling / Vernier microscope Make: RADICAL Instrument) was used to observed the macrostructure and check for any defects.

The transverse and all weld tensile testing was carried out on the coupons extracted from the welded plate. Four specimens were tested as per API (2 samples) and ISO (2 samples) to check the reproducibility of the results and average values were considered for analysis purpose. The samples were prepared from weld transversely as per the API 1104 standard wherein all the three zones (weld, HAZ and base metal) were covered and tested at room temperature. In order to check the suitability of the
metal cored consumable wire for the weld joint, all weld tensile testing was also carried out in as-welded conditions, wherein the specimen was extracted longitudinally in a way that the gauge length consisted primarily of the weld zone and weld + fusion line to check the HAZ properties. The impact toughness properties of the welded joint was carried out using Charpy V Notch testing procedure. The impact specimen with dimensions 55 mm x 10 mm x 10 mm was extracted from the weld joint in the transverse direction as per ASTM E23 standard. In order to test the toughness properties of the weld zone, V-notch was prepared within the weld after etching the sample so that the crack progresses in the weld zone on impact from hammer. Four sets (3 nos. Each set) of samples were tested for each condition and average values were considered for analysis purpose. Impact specimen were extracted from as welded condition.

3. Outcome and analysis

3.1 Macrostructure of weldment

The macrostructure of the welded joint is as shown in figure 5. The root pass was deposited using the RMD technique and in order to fill the weld groove subsequent passes were deposited using GMAW-P process incorporating metal cored wires. A traditional similar weld edge preparation selected for the study incorporates either root pass with SMAW/GTAW and GMAW process with solid filler wire. However, for 10.3 mm thick weld joint total 5-6 passes are required to be deposited. Macrostructure shown in Fig 5 was free from any defects and complete fusion on side walls were achieved on both the sides. The root pass deposited with RMD technique using metal cored filler wire showed complete depth of penetration which is one of the most noticeable output of the study.

![Figure 5. Macrostructure of welded joint](image)

3.2 Microstructure analysis

Weldment micro-structure was carried out to see any defects or imperfection at the interface. As shown in Fig 6, there is no any significant defect like lack of fusion observed in between weld and base metal interface, which ensures that welding parameters and consumables were used to weld X70 grade pipe was acceptable.
3.3 Vickers Hardness HV-10

Location of Vickers hardness on weld, base metal and HAZ are as shown in figure 7. Highest Vickers hardness values were in the HAZ zone around 225VHN compared to base metal and weld metal owing to un-tempered or coarse phases formed due to extremely rapid cooling. However, as shown in table 4, there are not much variation in hardness in all the zones like BM, HAZ and Weld.

![Figure 6. Microstructures of Interface (a) Base metal (b) HAZ (c) Weld zone](image)

![Figure 7. Microhardness survey across the weldments](image)
Table 4. Hardness values of Weld, HAZ and BM

|                  | Hardness Value |
|------------------|---------------|
| Weld (Top)       | 213, 215, 212 |
| Weld (Center)    | 212, 213, 210 |
| Weld (Bottom)    | 210, 212, 209 |
| Right HAZ (Top)  | 225, 224, 222 |
| Right HAZ (Center) | 224, 222, 221 |
| Right HAZ (Bottom) | 222, 221, 219 |
| Left HAZ (Top)   | 227, 225, 224 |
| Left HAZ (Center) | 225, 224, 222 |
| Left HAZ (Bottom) | 224, 222, 221 |
| Right BM (Top)   | 210, 211, 209 |
| Right BM (Center) | 212, 210, 211 |
| Right BM (Bottom) | 209, 212, 213 |
| Left BM (Top)    | 209, 210, 209 |
| Left BM (Center) | 207, 207, 206 |
| Left BM (Bottom) | 210, 211, 211 |

3.4 Tensile strength
The transverse and all weld tensile strength tested at room temperature and results are presented in Table 5. It is worth noting that all transverse tensile specimen failed from the base metal as shown in Table 5, indicating the weld was stronger than the base metal. In addition to this, the % elongation, in all weld tensile results shows that weld having enough or satisfactory ductile structure, which can give higher impact values. The results justify the selection of the combined RMD and GMAW-P technique, its corresponding parameters.

Table 5. Tensile test results

| Transverse tensile results | Ultimate tensile Strength MPa (Required 570-760 MPa) | Elongation (%) | Fracture location |
|---------------------------|-----------------------------------------------------|----------------|------------------|
| API-1                     | 625.3                                               | NA             | Parent           |
| API-2                     | 606.5                                               | NA             | Parent           |
| ISO-1                     | 624.8                                               | NA             | Parent           |
| ISO-2                     | 649.6                                               | NA             | Parent           |

| All weld tensile results | Ultimate tensile Strength MPa (Required 570-760 MPa) | Yield Strength (MPa) | Elongation (%) |
|--------------------------|-----------------------------------------------------|----------------------|----------------|
| As-welded                | 653                                                 | 581                  | 26.20          |
| As welded                | 689                                                 | 591                  | 28             |
In the current study, RMD and GMAW-P process have been proposed for welding with incorporating metal cored wires making the all weld tensile property a critical parameter. As depicted from table 5 the YS and UTS values are higher in as welded condition due to the fact that deposited filler metal area can be correlated with as quenched microstructure. During welding the filler metal is melted and deposited in the weld groove. During cooling the amount of relatively colder surroundings are quite high as compared to hotter molten mass. Hence the solidifying weld experience extremely faster cooling rates giving rise to harder untempered phases.

3.5 Impact strength
The impact testing was carried out at -60°C, -30°C and -45°C as shown in figure 9. The minimum requirement of the impact value of the weld joint was 27J as per code requirements. It could be seen from the figure 9 that the impact properties of the weld zone in as welded condition was found to be extremely higher than the required.

![Figure 8. Tested tensile specimen](image)

The toughness values are adequate for the joint to be used for end application ensuring safe working. The high toughness (> 27J required) of the weld zone confirms the successful implementation of RMD and GMAW-P technology using metal cored wires with selected parameters.

![Figure 9. Impact testing results](image)
3.6 Bend test
None of the root and face bend specimens after bend testing revealed any signs of cracking or tearing. Figure 10 shows all the bend samples, both in the root and face in as-welded conditions.

![Figure 10. Bend testing results](image)

3.7 Nick break test
4 Nos. of Nick break test specimens prepared as per API 1104 2005 Edition. As shown in figure 11, the exposed surfaces of each Nick-break specimen show complete penetration and fusion.

![Figure 11. Nick-break testing results](image)

3.8 Techno-Commercial evaluation
Time-comparison study on 24” OD X 10.3 mm thick X70 grade pipe shows that semi-automatic welding technique (RMD+GMAW-P) is 53% faster than SMAW process. Detail time study can be seen in the Table 6.

| Weld passes                  | Weld, Grinding and cleaning time (Minutes) |
|-----------------------------|------------------------------------------|
|                             | RMD+GMAW-Pulse | SMAW        |
| Root                        | 15            | 30          |
| First filler(F-1)           | 8             | 18          |
| Second filler (F-2)         | 10            | 21          |
| First capping (C-1)         | 6             | 9           |
| Second capping (C-2)        | 9             | 12          |
| Total time (Minutes)        | 48            | 90          |

Table 6. Time comparison between RMD + GMAW-P Vs SMAW
4. Conclusions

- The proposed combined approach of RMD and GMAW-P technique with seamless metal cored wire as a filler wire was successfully developed with required mechanical and metallurgical properties.
- The yield strength values of the welded joint 560 MPa, which was well above required as per construction codes and the impact value of weld at -60°C test temperature was achieved 145 J, which ensures enough ductility in weld metal and sustain high seismic load during service condition.
- A semi-automatic welding techniques feeds wire continues with much higher welding current and speed than SMAW, therefore it improves welding efficiency and reduces joints, greatly raising the qualification rate. It has little investment in equipment, high utilization rate, short payback period, and is cost-effective in quality, efficiency, material consumption and energy-usage, conforming to the concept of low-cost semi-automatic welding. Same would be confirmed from the time comparison study shown in table 6, which was evaluated against traditional pipeline welding process (SMAW).
- The Semi-automatic welding technology and groove types of X70 grade steel pipe have undergone strict welding evaluation and plentiful practical application. For this reason, it conforms to the characteristics of long-distance pipeline construction and the requirement of relevant design documents and standards, performing good welding quality.

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