Chapter 2 Literature Review

2.1 Pressure vessel steels

Pressure vessel and boiler quality steel are commonly found throughout the oil industry (including inshore and offshore), the petrochemical industry and the gas production industry. The companies in these industries set the highest demands in terms of quality, testing and conditions of supply have all the necessary expertise to meet these demands.

Different grades of steels such as ASTM A285, ASME SA285, ASTM A516, ASME SA516, ASTM A537, ASME SA537, EN 10028, BS 1501, DIN 17155 and Cryogenic Steels are used in the pressure vessels and boilers. SA516 steel plate is carbon steel with specifications for pressure vessel plates and moderate or lower temperature service. SA516 steel plate is intended primarily for service in welded pressure vessels where improved notch toughness is important. Plates 1.50” and under in thickness are normally supplied in the as-rolled condition. The plates may be ordered normalized or stress relieved, or both. Plates over 1.50” in thickness shall be normalized.

2.2 Overview on GMAW process

Introduction of GMAW process is presented in Chapter 1 via Fig: 1-1. GMAW also referees as metal inert gas (MIG) welding or metal active gas (MAG) welding, is a semi-automatic or automatic arc welding process wherein a continuous and consumable wire electrode and a shielding gas are fed through a welding gun [American Welding Society-welding hand book (1950), American Society of Metals Handbook-Welding, Brazing and Soldering (1993), Craig, E. (1991), Myers, D. (2014), Ahmed, N. (Ed.). (2005)]. It is a constant voltage, direct current power source process in a most common, but constant current systems, as well as alternating
current, can be used. GMAW welding gun, wire feed unit, electrode holder, power supply, electrode and shielding gas unit are the main components of GMAW [Ahmed, N. (Ed.). (2005) and Jeffus, L. (1997)]. These components are briefly discussed in the section of section of 2.1.1.

2.1.1 Components of GMAW process

GMAW gun and wire feed unit
The typical GMAW gun consists of number of sub components such as (1) torch handle, (2) molded phenolic dielectric and threaded metal nut insert, (3) shielding gas diffuser, (4) contact tip, (5) nozzle output face control switch, (6) power cable, (7) electrode conduit and liner, and (8) gas hose. Out of all these sub components, Fig: 2-1 (1-5) shows the components of GMAW torch nozzle [Mysid (2008)].

The wire feed unit is use to supply the electrode to the work. Mostly, constant feed rate is provided, however, it can be varied and applied to an advanced level machines where arc length and voltage are varying continuously.

Fig: 2-1 GMAW torch nozzle: (1) Torch handle, (2) Molded phenolic dielectric and threaded metal nut insert, (3) Shielding gas diffuser, (4) Contact tip, (5) Nozzle output face [Mysid (2008)]

Electrode
In case of GMAW, electrode holder is mostly semiautomatic type and air-cooled holder in which compressed air is circulated to maintain the temperature [American Welding Society-welding hand book (1950), American Society of Metals Handbook-Welding, Brazing and
This air cooled type electrode holder is generally used for butt joint and lap joint configurations with low current capabilities. Another water cooled type semiautomatic electrode is also available which can be used for the higher current applications especially for corner joint and T joint configurations. Water cooled automatic electrode holder is used for automated equipment [Mysid (2008)].

**Power supply**

GMAW operated on a constant voltage power supply as wire feeding is automated and continuous. Therefore, it means that arc length directly depends on voltage wherein, change in length of arc leads to the change in heat and current. A small arc length provides higher heat input that consequently leads to more melting of electrode and results into originally settled arc length. This is how consistent arc length is obtained even at the manual hand torch GMAW. Sometimes, constant current power source is used for the rare application [American Welding Society-welding hand book (1950), American Society of Metals Handbook-Welding, Brazing and Soldering (1993), Craig, E. (1991), Myers, D. (2014), Ahmed, N. (Ed.). (2005), Mysid (2008)].


**Shielding gases**

Shielding gases are used to protect the welding area from atmospheric contaminants. Improper shielding can cause different defects such as porosity, weld metal embrittlement and other fusion welding defects [American Welding Society-welding hand book (1950), American Society of Metals Handbook-Welding, Brazing and Soldering (1993), Craig, E. (1991), Myers, D. (2014), Ahmed, N. (Ed.). (2005), Vaidya (1996)]. In case of GMAW, the electrode wire is fed to the workpiece along with a separate shielding gas employed to protect the weld as it surrounds electrode wire. Due to shielding gas the slag formation problem associated with
shielded metal arc welding can be certainly avoided [American Welding Society-welding hand book (1950), American Society of Metals Handbook-Welding, Brazing and Soldering (1993), Craig, E. (1991), Myers, D. (2014), Ahmed, N. (Ed.). (2005), Vaidya (1996)]. However, the selection of shielding gas is important as suitability to workpiece material and several other factors of the process needs to be checked in order to avoid the defect formation. Shielding gases such as helium, argon, carbon dioxide and its mixtures in different proportion are employed as most commonly used shielding gases wherein helium and argon are known as inert gases while carbon dioxide is metal active gas [Myers, D. (2014), Vaidya (1996)]. Also, different combinations of shielding gas mixture are investigated as example mixture of argon, oxygen, helium, hydrogen and nitrogen is reported as effective for stainless steel material. Mixtures of argon, carbon dioxide and oxygen are marketed for welding steels. Other mixtures add a small amount of helium to argon-oxygen combinations, these mixtures are claimed to allow higher arc voltages and welding speed. Helium also sometimes serves as the base gas, with small amounts of argon and carbon dioxide added. However, because it is less dense than air, helium is less effective at shielding the weld than argon, which is denser than air. It also can lead to arc stability and penetration issues, and increased spatter, due to its much more energetic arc plasma. Helium is also substantially more expensive than other shielding gases. Other specialized and often proprietary gas mixtures claim even greater benefits for specific applications Metal transfer mode such as spray transfer, globular transfer and short circuit transfer is readily affected by shielding gases [American Welding Society-welding hand book (1950), American Society of Metals Handbook-Welding, Brazing and Soldering (1993), Craig, E. (1991), Myers, D. (2014), Ahmed, N. (Ed.). (2005), Vaidya (1996)]. Explanation of different metal transfer modes is presented in section 2.1.3.

### 2.1.2 Electrode wire

There are three types of the consumable electrodes used in gas metal arc welding process, which includes solid, flux cored and metal cored wire [American Welding Society-welding hand book (1950), American Society of Metals Handbook-Welding, Brazing and Soldering (1993), Craig, E. (1991), Ahmed, N. (Ed.). (2005)]. Flux cored and metal cored wires are called tubular type electrodes in which flux powder and metal powder is filled inside the metallic tube respectively, whereas solid wire is core of metallic material (see Fig: 2-2).

GMAW of mild steel and high strength steel commonly uses solid wires and flux-cored wires.
Solid wires are used mainly in steel structures and construction machineries. This is particularly because solid wires generate little slag and, thus, are more suitable for automated multiple-pass welding. These wires are available in several package forms such as spools for general uses and pail packs for automated processes.

(a) [Kapustka, N. (2012)]

(b) [American Welding Society-welding hand book (1950)]

Fig: 2-2 (a) Construction and (b) cross section of different filler wires of electrode

**Solid wires**

Some types of solid wires are designed to be more suitable for CO$_2$ gas shielding, while some other types are designed to be more suitable argon - CO$_2$ mixture of gas shielding in GMAW [American Welding Society-welding hand book (1950), American Society of Metals Handbook-Welding, Brazing and Soldering (1993), Craig, E. (1991), Ahmed, N. (Ed.). (2005)]. Chemical reaction between molten metal and shielding gas affects process performance. The yield ratio of chemical elements directly affects the mechanical properties of the deposited
metal as shown in Fig: 2-3 [Shinagawa-Ku (2011)]. Some types of wires are suitable for high welding currents, while some other types are suitable for low welding currents. This is because some brands of wires are designed suitable for sheet metals used in, for example, automobile application, and some other brands of wires suit for thick metals used in, for example, steel structures and pressure vessels applications. Sheet metals use low currents to prevent burn through, while thick metals use high currents to provide good penetration and high welding efficiency. The choice of high or low currents also depends on the welding position and shielding gas associated with the metal transfer mode [Shinagawa-Ku (2011)]. Therefore, in order to select a suitable solid wire, one need to taking into account the type of shielding gas to be used, process parameters and desired performance of the process.

![Graph](image1)

Fig. 2-3 Yield ratios of chemical elements as a function of CO₂ % in an Ar/CO₂ mixture

[Shinagawa-Ku (2011)]

**Advantages** [American Society of Metals Handbook, (1993)]

1. Electrode length does not face the restrictions encountered with Shielded Metal Arc Welding (SMAW).
2. Welding can be accomplished in all positions, when the proper parameters are used, a feature not found in Submerge Arc Welding (SAW).
3. Welding speeds are higher than those of the SMAW process.
4. Deposition rates are significantly higher than those obtained by the SMAW process.
5. Continuous wire feed enables long welds to be deposited without stops and starts.
6. Penetration that is deeper than that of the SMAW process is possible, which may permit the use of smaller sized fillet welds for equivalent strengths.
7. Less operator skill is required than for other conventional processes, because the arc length is maintained constant with reasonable variations in the distance between the contact tip and the work piece.
8. Minimal post weld cleaning is required because of the absence of a slag

**Disadvantages** [American Society of Metals Handbook, (1993)]

1. The welding equipment is more complex, usually more costly, and less portable than SMAW equipment.
2. The process is more difficult to apply in hard to reach places because the welding gun is larger than a SMAW holder and must be held close to the joint (within 10 to 19 mm) to ensure that the weld metal is properly shielded.
3. The welding arc must be protected against air drafts that can disperse the shielding gas, which limits outdoor applications unless protective shields are placed around the welding area.
4. Relatively high levels of radiated heat and arc intensity can hinder operator acceptance of the process.

**Applications** [American Welding Society – Welding Hand book, (1950)]

1. The process can be used for the welding of carbon and low alloy steels, stainless steels, aluminum, magnesium, copper, nickel and their alloys, titanium, etc.
2. For welding tool steels and dies.
3. For the manufacture of refrigerator parts.
4. MIG welding has been used successfully in industries like aircraft, automobile, pressure vessel and ship building.

**Flux cored wire**

Flux-Cored Arc Welding (FCAW) is defined as an arc welding process that uses an arc between a continuous filler metal electrode and the weld pool. The process is used with flux powder contained inside the tubular electrode, with or without additional shielding from an externally
supplied gas, and without the application of pressure. FCAW is also known as Cored-Rod Welding or Cored-Wire Welding. FCAW can be operated in semi-automatic modes. For all commercially important metal such as carbon steel, high strength alloy steel, stainless steel, aluminum, copper, etc can be welded in all positions with this process by choosing the appropriate shielding gas, electrode and all other welding variables [American Welding Society – Welding Hand book, (1950)].

Flux-cored wires (FCW) can be further classified into three types such as rutile type, basic type, and metal type. FCWs consist of a steel sheath and a cored flux that contains various chemical ingredients such as deoxidizer, arc stabilizer, slag former and metal powder (alloying element and iron power) to obtain desired chemical and mechanical properties of the deposited metal, usability, and welding efficiency. Rutile-type FCWs contain rutile-based flux. Basic-type FCWs contain lime-fluoride-based flux. Rutile-type FCWs offer excellent usability, while basic-type FCWs offer superior crack resistance. In contrast, the major flux ingredient of metal-type FCWs is metal powder that becomes part of the deposited metal, causing little slag covering. The constituents in the flux influence the characteristics of the arc and its welding performances. It can increase penetration, clean foreign matter from the work piece surface, influence the speed of welding and consequently affects the mechanical properties of the weld deposit [American welding society-welding hand book (1950), American Society of Metals Handbook-Welding, Brazing and Soldering (1993), Craig, E. (1991), Ahmed, N. (Ed.). (2005), Jeffus et al. (2009), Kah et al. (2013), Meyer et al. (1993)].

The FCAW process typically generates more fumes and spatters relative to solid wires when use of shielding gases are same. However, recent developments have resulted in the production of a new generation of cored wires with significantly reduced levels of welding fume. Table 2-1 shows a qualitative comparison between the GMAW, FCAW and MCAW on welding performance, including that of solid wires for reference [Jeffus et al. (2009), Kah et al. (2013), Meyer et al. (1993)].

**Advantages** [American Society of Metals Handbook, (1993)]

Because it combines the productivity of continuous welding with the benefits of having a flux present, the FCAW process has several advantages relative to other welding processes. These advantages include:
1. High deposition rates, especially for out-of-position welding
2. Less operator skill required than for gas-metal arc welding (GMAW)
3. Simpler and more adaptable than submerged arc welding (SAW)
4. Deeper penetration than shielded metal arc welding (SMAW)
5. More tolerant of rust and mill scale than GMAW.

**Disadvantages** [American Society of Metals Handbook, (1993)]
1. Slag must be removed from the weld.
2. More smoke and fume are produced in FCAW than in the GMAW and SAW Processes
3. Fume extraction is generally required
4. Equipment is more complex and much less portable than SMAW equipment.

1. Flux-cored arc welding enjoys widespread use in many industries. Both the gas-shielded and self-shielded FCAW processes are used to fabricate structures from carbon and low-alloy steels. Both process variants are used for shop fabrication, but the self-shielded FCAW process is preferred for field use. The acceptability of the FCAW process for structural use is illustrated by the fact that prequalified joints are included in the structural welding code of the American Welding Society (AWS).
2. Gas-shielded flux-cored electrodes are commonly used to weld carbon, low-alloy steel and stainless steels in the construction of pressure vessels and piping for the chemical processing, petroleum refining, and power-generation industries. In addition, flux-cored electrodes are used to weld some nickel-base alloys.
3. Flux-cored electrodes are also used in the automotive and heavy-equipment industries in the fabrication of frame members, axle housings, wheel rims, suspension components, and other parts. Small-diameter flux-cored electrodes are used for automotive body repair.

**Metal cored wire**
Tubular wires whose core consisted only of metallic ingredients in the tubular construction are called metal cored wires. It is generally used for hardfacing early in the history of the process, but afterwards the usage is expanded for different applications of welding. Improvement in the
process, productivity efficiency, cost effectiveness in terms of weld quality productivity. The internal components of a metal cored wire are composed chiefly of the alloys commonly manganese, silicon, and in some cases, nickel, chromium and molybdenum as well as small amount of arc stabilizers such as sodium and potassium, with the balance being iron powder. These alloying materials provide arc stabilization and fluxing of oxides [American welding society-welding hand book (1950), American Society of Metals Handbook-Welding, Brazing and Soldering (1993), Craig, E. (1991), Ahmed, N. (Ed.). (2005)].

Metal-cored wires provide high deposition rates with excellent deposition efficiency and can be used to weld in all positions. Flux cored wires provide better metal penetration, smoother arc transfers, lower spatter levels and overall easier than the solid wires [American welding society-welding hand book (1950), American Society of Metals Handbook-Welding, Brazing and Soldering (1993), Craig, E. (1991), Ahmed, N. (Ed.). (2005)].

The advantages of metal-cored wire are:
1. High deposition rates.
2. High deposition efficiency.
3. Quality welds over rust and mill scale.
4. Higher depth of fusion.
5. Low spatters level.
7. Easy to use.
8. All-position welding possible with short circuit metal transfer mode.
9. Lower fume levels.

The outer metallic sheath of a cored wire conducts the maximum of the electrical current during welding. Because of the fabricated, composite nature of cored wires, their current carrying density is greater, which improves deposition rates at equal current levels when compared to solid wires [Craig, E. (1991)]. Metal Cored wires have a maximum current density among all these three type of wires, which subsequently results in higher deposition rates, better penetration and better side wall fusion.


The advantages of metal-cored wire are:
1. High deposition rates.
2. High deposition efficiency.
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4. Higher depth of fusion.
5. Low spatters level.
7. Easy to use.
8. All-position welding possible with short circuit metal transfer mode.
9. Lower fume levels.
1. High initial cost of metal cored wire.
2. The new generation of metal core wire requires special production technology to assure low fume generation rates while maintaining high levels of weld quality.
3. For an operation point of view, metal core wires shielded by argon base shielding gases will generate a higher intensity of ultraviolet radiation when compared to CO$_2$ shielded flux cored wires.
4. Equipment cost is very high.
5. Removal of Silica Island becomes cumbersome with increasing CO$_2$ content in Ar-CO$_2$ mixture.

Metal cored wires are available to suit a variety of applications from high-speed general purpose welding to low temperature and high strength requirements.
1. Because it is relatively easy to adjust alloy compositions, metal cored wires are being found in new areas of applications like thermal spray process to develop a wide variety of corrosion and wear resistance areas on complex fabricated structures.
2. A new class of wires is also being developed to join several high strength steels where the cost of solid filler wire is very high and where the actual alloy compositions are difficult to obtain.
3. To join heavy sections plate because of its characteristics of high deposition rate and high travel speed [Jeffus, L. (1997)]
4. The metal core produces an exceptionally high recovery, enabling approximately 95% of the wire weight to be deposited as weld metal.
5. Used in conjunction with argon rich gases containing 15/25% CO$_2$ weld deposits of smooth consistent finish with minimal spatter and slag are easily produced.
6. Fume levels are significantly lower than those of conventional flux core wires and approximately 50% less than high recovery iron powder manual arc electrodes.
7. Weld metal savings of up to 30% can be achieved on single pass fillets through deep penetration which increases the effective throat thickness with a corresponding reduction in leg length of up to 20%.
8. Further economies can be realized by a reduction in deposited weld metal through the use of smaller preparation angle.
9. Metal cored wires produce low hydrogen quality weld metal.
10. Metal cored wires have the advantage in catering for the majority of down hand [Yuan et al. (2012)]

Table: 2-1 Comparison between GMAW, FCAW and MCAW

<table>
<thead>
<tr>
<th></th>
<th>GMAW</th>
<th>FCAW</th>
<th>MCAW</th>
</tr>
</thead>
<tbody>
<tr>
<td>Type of wire</td>
<td>Solid wire</td>
<td>Flux cored wire</td>
<td>Metal cored wire</td>
</tr>
<tr>
<td>Current density</td>
<td>287.5 A/mm²</td>
<td>376 A/mm²</td>
<td>480 A/mm²</td>
</tr>
<tr>
<td>[Yuan et al. (2016)]</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>For 1.2 mm dia wire</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Travel speed</td>
<td>Same</td>
<td>Same</td>
<td>Highest</td>
</tr>
<tr>
<td>[Jeffus, L. (1997), Mirza et al. (2013)]</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Metal transfer</td>
<td>- Dip transfer</td>
<td>- Dip transfer</td>
<td>- Globular transfer</td>
</tr>
<tr>
<td>[Mirza et al. (2013)]</td>
<td>- Globular transfer</td>
<td>- Globular transfer</td>
<td>- Spray transfer</td>
</tr>
<tr>
<td>- Spray transfer</td>
<td>- Pulsed transfer</td>
<td>- Not true spray transfer</td>
<td>- Pulse transfer</td>
</tr>
<tr>
<td>Spatter level - Ar based shielding</td>
<td>Higher</td>
<td>No spatter</td>
<td>Lower</td>
</tr>
<tr>
<td>[Jeffus, L. (1997)]</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fume level [Jeffus, L. (1997)]</td>
<td>Lower fume rate</td>
<td>High fume level</td>
<td>20-50% lower than Flux cored wire</td>
</tr>
<tr>
<td>Slag formation</td>
<td>Hardly found</td>
<td>High slag formation</td>
<td>Little silica island is found</td>
</tr>
<tr>
<td>[Jeffus, L. (1997)]</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Inter pass cleaning</td>
<td>Minimal</td>
<td>Must require</td>
<td>Minimal</td>
</tr>
<tr>
<td>[Jeffus, L. (1997)]</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Bead appearance</td>
<td>Some spatter shown on bead surface</td>
<td>Very Good</td>
<td>Good</td>
</tr>
<tr>
<td>[Jeffus, L. (1997)]</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Shielding gas</td>
<td>Require</td>
<td>For self shielded flux cored wire - does not require</td>
<td>Require</td>
</tr>
<tr>
<td>Deposition rate</td>
<td>3.3 kg/hr</td>
<td>3.8 kg/hr</td>
<td>5.2 kg/hr</td>
</tr>
<tr>
<td>1.2mm dia [Yuan et al. (2016)]</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Deposition efficiency</td>
<td>95 -98%</td>
<td>84-89%</td>
<td>92-98%</td>
</tr>
<tr>
<td>1.2 mm dia wire &amp; spray transfer mode [Jeffus, L. (1997)]</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Metallurgical benefits [Jeffus et al. (2009)]</td>
<td>Not any alloying element which give benefits</td>
<td>Flux composition supported mechanical properties</td>
<td>Add alloying elements for improve mechanical properties</td>
</tr>
<tr>
<td>-----------------------------------------------</td>
<td>---------------------------------------------</td>
<td>-------------------------------------------------</td>
<td>-----------------------------------------------------</td>
</tr>
<tr>
<td>Ultraviolet radiation [Jeffus, L. (1997)]</td>
<td>Low radiation</td>
<td>Low radiation</td>
<td>Very high with Ar-CO$_2$ mixture</td>
</tr>
<tr>
<td>Cost of wire [Jeffus, L. (1997)]</td>
<td>Cheap compare to metal cored &amp; flux cored wire</td>
<td>Little bit costly compare to solid wire</td>
<td>20-25% high compare to flux cored wire</td>
</tr>
<tr>
<td>Weld Economy [Jeffus, L. (1997)]</td>
<td>Less economical compare to metal cored arc welding for high section thickness</td>
<td>Not economical for high section thickness</td>
<td>Most Economical for high section thickness</td>
</tr>
<tr>
<td>Hydrogen induced [Vaidya (1996)]</td>
<td>Low</td>
<td>High</td>
<td>Low</td>
</tr>
<tr>
<td>Duty cycle and travel speed [Jeffus, L. (1997)]</td>
<td>High duty cycle and low travel speed</td>
<td>Low duty cycle and low travel speed</td>
<td>High duty cycle and high travel speed</td>
</tr>
</tbody>
</table>

### 2.1.3 Basic variables of GMAW

There are some basic variables of GMAW such as welding current, arc voltage, polarity, travel speed, metal transfer mode, and electrode wire, which affect the weld performance and properties such as penetration, bead geometry and overall weld quality. These variables of GMAW also influence each other significantly. Discussion on basic variables of GMAW are presented as under.

**Welding Current**

Most important factor of GMAW process is welding current. It depends on electrode wire feeding speed and melting rate of electrode mainly. When all other variables are held constant, an increase in welding current results in an increase in the depth and width of penetration, deposition rate, and weld bead size [American Society of Metals Handbook-Welding, Brazing and Soldering (1993)]. As the electrode feed speed varies, the welding current also varies in a like manner when a constant voltage power source is used. This is because the current output of the power source varies dramatically with the slight change in the arc voltage (arc length), and that result when changes are made in the electrode feed speed [American welding society-welding hand book (1950), American Society of Metals Handbook-Welding, Brazing and Soldering (1993), Craig, E. (1991), Ahmed, N. (Ed.). (2005)]. For all other constant process parameters, welding current increases as feeding of wire electrode increases. Suitable welding
current is chosen based on type of workpiece being welded and its thickness. Combinations of all other process parameters are also important along with favourable welding current.

For given current, higher current density is obtained by metal cored wire relative to flux cored and solid wires. This leads to high deposition rates of metal cored wire compares to flux cored and solid wires. The reason for the higher current density is construction of the electrode. Metal cored wire is made up of tubular wire and metal powder inside the tube. Hence, current is only carried away by metallic tubular part as it is tubular construction. So, the current density is high in case of metal cored wire. One of the case study of different deposition rates reported in the literature is presented in the Table 2-2.

Table 2-2 different depositions rates for different electrode filler wires [Yuan et al. (2016)]

<table>
<thead>
<tr>
<th>Electrode/Wire</th>
<th>Diameter (mm)</th>
<th>C/S area (mm²)</th>
<th>Current (A)</th>
<th>Current Density (A/mm²)</th>
<th>Deposition rate (kg/hr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>FCAW wire (E71T-1)</td>
<td>1.2</td>
<td>0.625</td>
<td>235</td>
<td>376</td>
<td>3.8</td>
</tr>
<tr>
<td>MIG wire (ER70S-6)</td>
<td>1.2</td>
<td>1.130</td>
<td>235</td>
<td>287.5</td>
<td>3.3</td>
</tr>
<tr>
<td>MCAW wire (E70C-6M)</td>
<td>1.2</td>
<td>0.625</td>
<td>300</td>
<td>480</td>
<td>5.2</td>
</tr>
</tbody>
</table>

Voltage

Voltage of the arc and process affects the energy provided for to fuse the material that affects the properties of welds and weld bead profile. Weld bead width is mostly affected by the working voltage and arc voltage. Arc voltage has a direct influence on the arc length that subsequently controls the weld shape, depth of penetration and spatter level. As the arc voltage is reduced the penetration of weld increases [American welding society-welding hand book (1950), American Society of Metals Handbook-Welding, Brazing and Soldering (1993), Craig, E. (1991), Ahmed, N. (Ed.). (2005)].

Although the arc length is the variable of interest and that needs to be controlled in order to have better welds. However, direct way of controlling arc length is control the arc voltage. For any specific value of arc voltage, an increase tends to flatten the weld bead and that increases the width of the fused zone. Excessive high voltage can cause defects such as porosity, spatter,
and undercut. Whereas, the excess reduction in voltage results in a narrower weld bead with a higher crown [American Society of Metals Handbook-Welding, Brazing and Soldering (1993)].

**Polarity**

Polarity is used to describe the electrical connection of the welding gun with relation to the terminals of a direct current power source. When the gun power lead is connected to the positive terminal, the polarity is designated as direct current electrode positive (DCEP), which is arbitrarily called reverse polarity. Whereas, when the gun is connected to the negative terminal, the polarity is designated as direct current electrode negative (DCEN), which is called straight polarity. Maximum heat is generated at the positive terminal due to flow of electron is directed towards the positive charge through negative charge [American welding society-welding hand book (1950), American Society of Metals Handbook-Welding, Brazing and Soldering (1993), Craig, E. (1991), Ahmed, N. (Ed.). (2005), Mysid (2008), Vaidya (1996), Kapustka, N. (2012), Shinagawa-Ku (2011)].

**Travel speed**

Travel speed is the linear rate at which the welding torch is moving along the weld joint. With all other variables held constant, weld penetration is a maximum at an intermediate travel speed. Lower travel speed results in higher heat input while higher welding speed leads to lower heat input. Hence, optimum welding speed with respect to the heat input conditions is recommended considering process conditions, workpiece material and its thickness [American welding society-welding hand book (1950), American Society of Metals Handbook-Welding, Brazing and Soldering (1993), Craig, E. (1991), Ahmed, N. (Ed.). (2005), Mysid (2008)].

**Electrode extension**

The electrode extended is nothing but the distance from the end of the contact tip to the arc (refer Fig: 2-4), which is sometimes refereed as electrical stick-out, mostly in the industries. The electrode extension includes only the length of the electrode, not the extension plus the length of the arc. An increase in electrode extension causes an increased electrical resistance that in turn, generates additional heat at the electrode, which contributes to greater melting of electrode. Hence, it affects the performance of the weld bead and weld properties [American welding society-welding hand book (1950), American Society of Metals Handbook-Welding, Brazing and Soldering (1993), Craig, E. (1991), Ahmed, N. (Ed.). (2005), Mysid (2008)].
Similarly, any decrease in the electrode extension will have the effect of increasing welding current and this characteristic can be of benefited in controlling penetration, especially where inconsistence fit up is encountered [Yuan (2012)].

During actual welding any large variation will produce an inconsistent weld deposit and an excessive electrode extension has the effect of reducing the amperage drawn from the power source. Increasing the wire feed speed to compensate for the current drop will result in a significant increase in weld metal deposition [American welding society-welding hand book (1950), American Society of Metals Handbook-Welding, Brazing and Soldering (1993), Craig, E. (1991), Ahmed, N. (Ed.). (2005), Mysid (2008)].

Electrode diameter
The electrode diameter largely influences the weld bead configurations. A larger diameter electrode requires a higher electrical current than a smaller electrode in order to achieve the same metal transfer characteristics that in turn, produce an additional electrode melting and hence can obtain larger sized fluid welds deposits. Higher currents also result in higher
deposition rates and greater penetration. The wire diameter has also influenced on the melting rate. The melting rate of cored wire is much higher than solid wire as shown in Fig: 2-5 [American Society of Metals Handbook-Welding, Brazing and Soldering (1993)].

Melting rate is defined as the mass of the filler metal melted in a unit of time. It is the most important factor in assessing the productivity of a welding process. The electric energy introduced in a welding process transforms into thermal energy, which increases the energy of the filler material up to the melting point. A droplet is formed and passes through the arc into the weld pool. Melting rate is mainly affected by welding current, I (A), but the influence of the wire extension length, L (mm) and wire diameter, d (mm) should not be neglected since the wire heats because of ohmic resistance [American welding society-welding hand book (1950), American Society of Metals Handbook-Welding, Brazing and Soldering (1993), Craig, E. (1991), Ahmed, N. (Ed.). (2005), Mysid (2008), Vaidya (1996), Kapustka, N. (2012), Shinagawa-Ku (2011)].

The increase in filling ratio actually reduces wire current-carrying cross-section and, consequently, increases the melting rate. The core of the cored wire, does not conduct or only partially conducts electric current, therefore, current density is increased. With the increase in the wire diameter for a same current level, the melting rate is reduced [Yuan et al (2014)].
Workpiece preparation
Due to the superior side wall fusion obtained particularly from the metal cored wires the combined angles of preparations can generally be reduced. A V-butt joint for instance that would normally need a 60° included angle for manual arc welding can be reduced to 45° (as shown in Fig: 2-6), thereby saving plate and hence weld metal to fill the joint.

The higher levels of de-oxidation and higher current density available with cored wires allows them to be used where mill scale and primer have to be tolerated. This is particularly so with the metal and basic cored wires, since the rutile types are the least tolerant from one side with backin [Yuan et al. (2012)].

![Single v-groove joints welded](image1)

![Narrower groove angle for FCAW](image2)

Fig: 2-6 Plate preparation. [Yuan et al (2013)]

Because of the deep penetration characteristic of FCAW, no edge bevelling preparation is required on some joints in metal up to 1/2 in. (13 mm) in thickness. When bevels are cut, the joint-included angle can be reduced to as small as 35°. The reduced groove angle results in a smaller-sized weld. This can save 50% of filler metal with about the same savings in time and weld power used. The narrower groove angle for FCAW compared to other welding processes saves on filler metal, welding time, and heat input into the part [Yuan et al. (2013)].

Electrode orientations and applications.
The orientation of the welding electrode wire with respect to the weld joint affects the weld bead shape and penetration. The electrode orientation is described in two ways: (1) the relationship of the electrode axis with respect to the direction of travel (travel angle: drag angle and push angle) and (2) the angle between the electrode axis and the adjacent work surface (work angle), as shown in Fig: 2-7.
Fig: 2-7 Definitions of work angle, drag angle, and push angle [Kita-Shinagawa (2012)]

In the “backhand” welding technique, the wire is pointed with a drag angle (10-20 degrees) towards the opposite of the travel direction. When the wire is pointed with a push angle (10-20 degrees) towards the travel direction, this manner is called the “forehand” welding technique. Each technique has advantages and disadvantages as summarized below, provided all other conditions are kept unchanged [American welding society-welding hand book (1950), American Society of Metals Handbook-Welding, Brazing and Soldering (1993), Craig, E. (1991), Ahmed, N. (Ed.). (2005), Mysid (2008), Vaidya (1996), Kapustka, N. (2012), Shinagawa-Ku (2011)].

**Metal transfer modes**

There are mainly metal transfer modes in GMAW known as globular mode, short-circuit mode, and spray transfer mode [Meyer, D.W. (1993)]. These different metal transfer modes are discussed as under.

**Globular metal transfer mode**

GMAW with globular metal transfer is considered the least desirable of the three major GMAW variations of solid wire, flux cored wire and metal cored wire, because of its tendency to produce high heat, a poor weld surface, and spatter formation phenomenon. However, the globular transfer mode is a cost efficient way to weld steel using GMAW, because this variation uses carbon dioxide, a less expensive shielding gas than argon [American welding society-welding hand book (1950), American Society of Metals Handbook-Welding, Brazing and
Soldering (1993), Mirza et al. (2009)]. In addition to economic benefit, it has high deposition rate that allows welding speeds up to 110 mm/s. A ball of molten metal from the electrode tends to build up on the end of the electrode as soon as the weld is made, often in irregular shapes with a larger diameter than the electrode itself. When the droplet finally detaches either by gravity or short circuiting, it falls to the workpiece, leaving an uneven surface and often causing spatter. As a result of the large molten droplet, the process is generally limited to flat and horizontal welding positions, requires thicker workpieces, and results in a larger weld pool [Mirza et al. (2009), Kah et al. (2013)].

**Short-circuiting**

Further developments in welding steel with GMAW led to a variation known as short-circuit transfer (SCT) or short-arc GMAW, in which the current is lower than for the globular method. As a result of the lower current, the heat input for the short-arc variation is considerably reduced, making it possible to weld thinner materials while decreasing the amount of distortion and residual stress in the weld area [Kah et al. (2013)]. As in globular welding, molten droplets form on the tip of the electrode, but instead of dropping to the weld pool, they bridge the gap between the electrode and the weld pool as a result of the lower wire feed rate. This causes a short circuit and extinguishes the arc, but it is quickly reignited after the surface tension of the weld pool pulls the molten metal bead off the electrode tip. This process is repeated about 100 times per second, making the arc appear constant to the human eye. This type of metal transfer provides better weld quality and less spatter than the globular variation, and allows for welding in all positions, albeit with slower deposition of weld material. Setting the weld process parameters (volts, amps and wire feed rate) within a relatively narrow band is critical to maintaining a stable arc. Also, using short-arc transfer can result in lack of fusion and insufficient penetration when welding thicker materials, due to the lower arc energy and rapidly freezing weld pool. Like the globular variation, it can only be used on ferrous metals [Mirza et al. (2009), Kah et al. (2013)].

**Spray Transfer mode**

Spray transfer GMAW was the first metal transfer method used in GMAW, and well-suited to welding aluminium and stainless steel while employing an inert shielding gas. In this GMAW process, the weld electrode metal is rapidly passed along the stable electric arc from the electrode to the workpiece, essentially eliminating spatter and resulting in a high-quality weld
finish as shown in Fig: 2-8 [Mirza et al. (2009), Kah et al. (2013), Yuan et al. (2016)]. As the current and voltage increases beyond the range of short circuit transfer the weld electrode metal transfer transitions from larger globules through small droplets to a vaporized stream at the highest energies. Since this vaporized spray transfer variation of the GMAW weld process requires higher voltage and current than short circuit transfer, and as a result of the higher heat input and larger weld pool area (for a given weld electrode diameter). Also, because of the large weld pool, it is often limited to flat and horizontal welding positions and sometimes also used for vertical-down welds. It is generally not practical for root pass welds. When a smaller electrode is used in conjunction with lower heat input, its versatility increases. Table: 2-3 represents metal transfer modes successfully possible for flux cored, metal cored and solid wires. It can be seen that, spray transfer is possible for solid wire and metal cored wire whereas globular transfer is possible for only flux cored wire. Moreover, dip transfer is possible by all the filler electrode wires of solid, flux cored and metal cored [American welding society-welding hand book (1950), Mirza et al. (2009), Kah et al. (2013), Yuan et al. (2016)].

Table: 2-3 Types of transfer mode for different types of wires [American welding society-welding hand book (1950), Yuan et al. (2016)]

<table>
<thead>
<tr>
<th>Process</th>
<th>Dip Transfer</th>
<th>Globular Transfer</th>
<th>Spray Transfer</th>
<th>Pulsed Transfer</th>
</tr>
</thead>
<tbody>
<tr>
<td>Metal Inert Gas (MIG)</td>
<td></td>
<td></td>
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<tr>
<td>Flux Cored (Gas Shielded)</td>
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<tr>
<td>Flux Cored (Self Shielded)</td>
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<tr>
<td>Metal Cored</td>
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</tr>
</tbody>
</table>
**Pulsed Transfer**

Pulsed arc welding is a controlled method of spray transfer, using currents lower than those possible with the spray transfer technique, thereby extending the applications of MIG welding into the range of material thickness where dip transfer is not entirely suitable. Fig: 2-9 shows the pulse transfer mode.
The pulsed arc equipment effectively combines two power sources into one integrated unit. One side of the power source supplies a background current which keeps the tip of the wire molten. The other side produces pulses of a higher current that detach and accelerate the droplets of metal into the weld pool. The transfer frequency of these droplets is regulated primarily by the relationship between the two currents. Pulsed arc welding occurs between ±50–220 A, 23–35 V arc volts and only with argon and argon based gases. It enables welding to be carried out in all positions [Mirza et al. (2009), Kah et al. (2013), Yuan et al. (2016)].

2.3 State of art on comparisons of GMAW, FCAW and MCAW

In this section state of art on comparisons of GMAW, FCAW and MCAW are presented. However, limited literature on comparisons of GMAW, FCAW and MCAW are available out of which some of the studies have been highlighted in the above sections. It has been reported that, comparisons on process performances, shielding gas effects, metal transfer mode, effect of welding variables and hybrid welding are reported so far, which are explained as under.

2.3.1 GMAW, FCAW and MCAW process comparisons
The construction of filler wire is the only difference in the basic set up of the GMAW technique aforementioned above. However, large variations in the process capabilities, performance and welds properties have been reported for GMAW, FCAW and MCAW. Some of the comparative key features are mentioned as under.

FCAW technique uses flux and gas dual shielding which provides extra shielding and restricts reactions with atmospheric gases that subsequently leads to the good quality joints without any defects. Whereas, processes such as GMAW and MCAW use single gas shielding in which the formation of defects due to reaction with atmospheric gases is having high chance relative to FCAW process.

FCAW process is advantages in terms of weld positions as this process is having phenomenon of slag former which allows the use of it at all the positions. The slag cover protects molten material by not allowing it to fall down even for the overhead position. On the contrary, MCAW and GMAW processes cannot be employed for all the positions as these processes are not
forming cover of slag over the weld bead. Nevertheless, the multi pass MCAW and GMAW are advantages due to this phenomenon of not forming slag cover while in case of FCAW, proper de-sludging is required after each and every weld pass in order to obtain quality weld.

MCAW is advantages in terms of weld having metal powder insertion inside it. Higher deposition rate and excellent weld bead profile can be obtained with the help of metal cored wire relative to GMAW and FCAW. Alloing elements used in metal cored wire can enhance the weld properties. The MCAW can provide additional advantages such as low slag, low spatter, high duty cycle and high volume of weld. Additionally, the travel speeds can often be raised by 30 % or more with the application of metal cored wire [Starling et al. (2010), Arivazhagan et al. (2013), Phillips et al. (2016), Garcia et al. (2011), Starling et al. (2011)].

Starling et al. (2011) and Starling et al. (2010) have compared the operational performances and bead characteristics for two different process variations of GMAW such as FCAW and MCAW. They have done analysis for MCAW and FCAW under different parameters such as welding current and voltage, operational stability, geometry, microstructure, hardness of the weld profile, effect of shielding gas and metal transfer modes. They have found that, average deposition rate, weld area and working current were reported higher in case of MCAW when all other process parameters were kept constant. Fluctuations of current and voltage values were reported with basic type flux cored filler wire. In addition to this, they have reported that, mixing of shielding gas significantly affected the properties of weld in case of MCAW and FCAW. The effect of welding speed was also investigated by these group for MCAW and FCAW.

Starling et al. (2011) and Starling et al. (2010) have carried out these studies with negative polarity and subsequently identified the remarkable influence of tubular cored wires on bead geometry and overall performance of operation. Mihăilescu et al. (2014) have compared FCAW and cored wire welding for coefficient of fusion and weld deposition through mechanized metal active gas welding process. The highest coefficient of melting was obtained in the case of basic type flux cored wire, while the layering coefficients were reported as lower for rutile type flux core wire.
2.3.2 Effect of shielding gas on GMAW, FCAW and MCAW

Shielding gases have great influence on GMAW, FCAW and MCAW process variations. Mukhopadhyay et al. (2006) have studied the effect of shielding gas compositions on HSLA steel using solid and flux cored filler wires of ER 70S6 and E71T-1M (1.2mm diameter) respectively. They have maintained 150°C inter pass temperature. Ternary gas mixtures were used with different proportions of Ar, CO₂ and O₂ for arc stability, mode of metal transfer, weld bead characteristics etc. During welding the shielding gas interact with the weld pool and the addition of CO₂ and O₂ in Ar causes oxidation, which result in some losses of alloying constitute and produce inclusions in the weld, which affects the weld properties. However, under this conditions, certain oxide inclusion promotes the formation of acicular ferrite phase, which improve toughness and may initiate premature ductile fracture. They reported that, microstructure primarily depends on chemical compositions and cooling rate. In weld metal it is also depended on the inclusions presented in the weld metal. The weld metal composition is the function of shielding gas compositions, welding wire, base metal and time allowed for reactions. The cooling rate is a direct function of heat input, plate thickness, the preheat temp, and the indirect function of current, voltage, and welding speed, and heat transfer efficiency. The weld metal chemical compositions are controlled by chemical reactions occurring in the weld pool at elevated temperature Mukhopadhyay et al. (2006). Two stages of reaction was described in the weld pool by authors such as (1) Just below the arc where the temperature was to be estimated approximately 2000°C, O₂ was dissolved in a great amount, since Si and Mn do not act as de-oxidant at temperature greater than 1800°C and (2) The cooling stage of the dissolve O₂ was rejected and it precipitates as micro particles. The loss of Mn and Si may be caused by oxidation reactions in the weld pool as shown below.

\[
\begin{align*}
\text{Si} + 2[\text{O}] &= \text{SiO}_2 \\
\text{Mn} + 2[\text{O}] &= 2\text{MnO}
\end{align*}
\]

A further decrease in the Si content takes place due to the presence of CO at the gas/ metal interface forming SiO according to the reaction.

\[
\text{SiO}_2 + \text{CO} = \text{SiO} + \text{CO}_2
\]

Similarly Mn could be lost further by vaporization due to its high vapor pressure. Here two different wires had the different amount of Mn, so the metal droplets transferred and the weld pool resulting from each wire had different Mn activity levels. But then after a similar loss of Mn was found for both wires that indicate the reaction involving Mn and O₂ was limited by the kinetics, not by Mn activity in metal. Increasing the O₂ activity of shielding gas increases the
weld metal $O_2$ content, as presented by the volume fraction of inclusions, since most of the $O_2$ combine with other elements to form oxides due to its low solubility in iron. Both filler wires had different volume fraction and size distribution of inclusions. In weld made with flux cored wire, the volume fraction of inclusion was higher than that in solid wire due to high alloying contents [Mukhopadhyay et al. (2006)].

The microstructures of both wires contained regions of acicular ferrite (AF), grain boundary ferrite (GF), and ferrite with side plate (FS). However, the total proportion of AF and FS appeared higher in the flux cored arc welds than solid wire welds. Transmission electron microscopy (TEM) reveals inclusions of varying size and distribution within the ferrite. Occasionally, an elongated inclusion was also observed but most of inclusions observed in TEM were spherical in size. For welds made with solid wire, the proportion of AF progressively increased with $O_2$ content in the shielding gas and the proportion of FS was decreased. For the weld made with flux cored wire, the proportion of AF decreased with an increased in $O_2$ or $CO_2$ contents of the shielding gas and GF increased [Mukhopadhyay et al. (2006)].

Increasing the $O_2$ content in the shielding gas from 2 % to 5 %, the size of inclusion increased from 0.4 to 0.8 micro meter and the inclusion volume fraction increased from 0.0012 to 0.0028. Increase in YS and UTS in solid wire up to 4 % $O_2$, was due to the increase in the proportion of AF due to its fine grain size and high dislocation density. However, a decrease in UTS and elongation at 5 % $O_2$ content was indicate that long ferrite veins which decorate the prior austenite grain boundary act as a preferential crack path through the microstructure. Decrease in the YS and UTS with increase in the $O_2$ content up to 4 % in flux cored wire was due to decrease in AF content. The impact properties of weld metals improved with the proportion of AF in as deposited regions [Mukhopadhyay et al. (2006)].

In addition to this, Vaidya et al. (1996) have described the effects of addition of oxygen and carbon dioxide to argon on arc stability for semiautomatic weld metals in steel, stainless steel, Al and high Ni alloys. They also discussed the effect of changing potential gas on the chemistry, mechanical properties and diffusible hydrogen contents of weld metal. They studied these effects for solid, flux cored and metal cored wire.
They studied the arc stability on carbon steel and stainless steel material using binary and ternary mixtures. In this type of arc welding, the shielding gas influences the size and shape of the plasma column. Arc stability depends on two important factors, like physical and chemical properties of the shielding gas mixture. Argon has low thermal conductivity compared to He and CO₂ at arc temperature. The plasma column with Ar shielding expands beyond the molten wire tip and extend upwards, creating more surface for electron condensation heating. That heating rapidly melts the wire, and produces a fine point at the end of wire. Simultaneously, in the presence of strong Lorentz forces, the rapid melting produces a fast stream of fine droplets, impinging on the base metal, producing deep directional penetration [Vaidya et al. (1996)].

MCAW and GMAW welding of carbon steels, with pure He or CO₂ produce an unstable globular arc transfer. Arc stabilization was confirmed by improved weld-bead wetting, thus producing a much wider weld-bead as gas transit from pure Ar to mixture. Addition of 1-2% O₂ to Ar gives beneficial stabilizing effect on welding arc. Beyond arc stabilization, the progressive addition of oxidizing species would contribute the loss of alloying element through welding arc. Also it would increase the fume generation [Vaidya et al. (1996)]. While welding carbon steel using MCAW and GMAW welding, the ternary mixture gives the optimized chemistry of shielding gas to provide maximum flexibility for process application and reduction in fume levels. The advantage of tri mixture resided in reduction of globular transfer, while providing lower voltages to initiate spray transfer. The same gas could be used for short circuit and pulse or spray transfer [Vaidya et al. (1996)]. Oxidation Potential (PO) is calculated by: % O₂ + ½ % CO₂. As the oxidation potential of shielding gas increases, the C, Si and Mn would be progressively lost therefore the strength of the weld will deteriorate [Vaidya et al. (1996)].

FCAW consumables also have many slag formers in the core that can be hygroscopic. Untreated rutile and arc stabilizing titanates can significantly contribute to humidity pick up over short time. Due to some of the above reasons, FCAW wires can display varying degrees of susceptibility to hydrogen pick up as observed by D.D. Hawing. Their work indicates that rutile FCAW wires after one week exposure to 80°F/80% R.H. conditions increased in the deposited diffusible hydrogen content of the weld mental from 4 to 8 ml/100g for one wire and 8 to 27 ml/100g for another wire respectively. Due to the lack of arc stabilizers and other non-metallic substances in the core, metal-cored wires are less susceptible to moisture pick up. The MCAW wire diffusible weld metal contents increased from 11 ml/100g to 12 ml/100g, after one-week
exposure to 80°F/80% R.H. conditions. The initial high level of hydrogen would be related to the manufacturing variables in the processing of the MCAW wires to contain less than 3 ml/100g of hydrogen in the weld deposit, consistently. All position rutile FCAW wires often display worm tracking porosity on the weld deposit, when the wire has absorbed moisture during inadequate storage. If worm tracking porosity is a persistent problem, and assuming that the wire cannot be changed due to a variety of reasons, these solutions may considered to reduce the worm tracking porosity.

Firstly, welding could be conducted at lower amperage but with a longer electrode stick out. The resistance heating of the wire extension may evaporate some of the moisture on the wire, before it enters the welding arc. Alternatively, the first two layers of the wire spool could be discarded and welds reattempted.

In the articles of Starling et al. (2011) and Starling et al. (2010), the research was carried out on a comparative study of the characteristics of the weld bead produced by tubular wires of E71T-5/ E71T-5M basic flux core wire, E71T-1/ E71T-9/E71 T-9M Rutile flux core wire and E70C-3M metal cored wire used for 12 mm thick structural steel plates with low and medium levels of carbon. The diameter of all wires was 1.2 mm. With each type of tubular wire, the shielding gas (75%Ar-25%CO₂ and 100% CO₂) and feed speed (7 m/min and 9 m/min) were varied and other parameters were kept constant like polarity was DCRP, electrode stick out was 16 mm and the arc length was 3.5 mm. There were 12 experiments (3 wires x 2 wire feed speed x 2 shielding gas) carried out. Two or more welds were produced for each experiment. For all tubular wires, the electrical resistance at fusion temperature was higher than ambient temperature. The electrical resistance of basic and rutile wire was lower than metal cored wire. Also for both temperatures, the resistance levels of basic and rutile wire was close.

The shadow-graphy technique was used to evaluate metal transfer. For rutile wire, for different current and for different shielding gas, globular metal transfer was observed and formation of column of flux projected towards weld bead. For basic wire, under the condition of low current and different shielding gases, metal transfer was globular repulsive and formation of column of flux projected towards weld bead and for the high current metal transfer was globular with 75 % Ar -25 % CO₂ shielding gas, and for 100 % CO₂ it was globular repulsive. For metal cored wire under 100 % CO₂ shielding gas and different current levels the metal transfer was globular
repulsive and for 75 % Ar- 25 % CO₂ at low current level it was globular and at high current level it was projected spray [Starling et al. (2011) and Starling et al. (2010)].

For the same shielding gas (75% Ar-25% CO₂ and 100% CO₂) and the same wire feed speed (7 or 9 m/min), the following results were reported. The avg. current value was greatest in welding with metal cored wire and lowest in basic wire welding. The avg. arc voltage was lowest in welding with rutile wire. The highest deposition rate occurred with metal cored wire. The welded area with the largest microstructure occurs for metal cored wire, while those in rutile and basic wires were refined. The highest hardness occurred with rutile wire while lowest with metal cored wire. In welding with 75% Ar-25% CO₂, and with the same wire feed speed (7 or 9 m/min), the following results were reported. The avg. value of arc was greatest with metal cored wire. The greatest fluctuations in welding current and arc voltage occurred with basic wire indicate the lowest operational stabilities for the same. The highest deposition efficiencies occurred with metal cored wire indicating the highest operational stabilities for the same. The weld beads with the most regular surfaces and the lowest level of spatter occurred with metal cored wire indicated the highest operational stabilities for the same. The highest values for the width, reinforcement, maximum penetration, deposited area, area of penetration and dilution occurred with the metal cored wire while the lowest values of reinforcement, deposited area and area of penetration occurred with rutile wire and the lowest value of maximum penetration and dilution occurred with basic wire. The largest fractions of primary ferrite with grain boundaries and of intra granular primary ferrite occurred with metal cored wire while lowest with rutile wire. The highest levels of ferrite with non-aligned secondary phase occurred with rutile wire while lowest with metal cored wire. In welding with 100% CO₂, and for the same wire feed speed (7 or 9 m/min), the following results were reported. The avg. arc voltage was highest in welding with basic wire. The lowest fluctuations in welding current and arc voltage occurred with rutile wire indicate the highest operational stabilities for the same. The greatest deposition efficiencies occurred with rutile wire and lowest with basic wire, indicate highest and lowest operational stabilities for the same respectively. The welds with most regular surface and the lowest levels of spatter occurred for the rutile wire indicates the highest operational stabilities for the same. The lowest values of deposition rate occurred with basic wire. The highest values for width, deposited area and area of penetration occurred with metal cored wire. The highest value of reinforcement occurred with the basic wire. The lowest value of width and deposited area occurred for basic wire. The lowest value of reinforcement,
maximum penetration, area of penetration and dilution occurred for the rutilec wire. The largest fractions of primary ferrite with grain boundaries and acicular ferrite occurred for rutile wire while the lowest with metal cored wire. The largest fractions of ferrite with non aligned secondary phase and intra granular primary ferrite occurred for metal cored wire. The lowest levels of ferrite with non-aligned secondary phase occurred for rutile wire [Starling et al. (2011) and Starling et al. (2010)].

For the same wire feed speed (7 or 9 m/min), the most suitable welding conditions involved the use of metal cored wire with 75% Ar-25% CO₂, if a high deposition rate associated with good operational stability, a good surface appearance of the weld bead, low levels of spatter and good penetration are the main requirement. Also the rutile wire in welding with 75% Ar-25% CO₂ is suitable when better mechanical properties in the welded zone associated with good operational stability, a good surface appearance of the weld bead and low levels of spatters are the main requirements [Starling et al. (2011) and Starling et al. (2010)].

Mirza et al. (1999) and Mirza et al. (2013) have studied, three types of welding wire, solid, metal cored, and rutile cored, were selected to study the effects of various combinations of shielding gases on the weld metal hydrogen content. The rutile flux cored wire was also tested using a variety of welding parameters to examine the effects of shielding gases with different heat inputs. When choosing a shielding gas to produce a lower weld metal hydrogen content, other factors should also be considered. The shielding gas should stabilise the arc and metal transfer, improve the performance and productivity, and reduce the risk of defects such as porosity and other fusion defects.

The required test pieces assemblies comprised run on and run off pieces with a central analysis. The assemblies were degassed at 650°C for 1 h in a constant flow of argon to minimise oxidation. The chemical composition of the steel used for the present work was (wt-%): Fe–0.12C–0.02Si–0.6Mn–0.14P–0.005S–0.03Cr–0.01Mo–0.03Ni–0.005Ti. Proprietary BOC welding gases were used, at a flow rate of 20 L/min, across wider ranges than normally recommended for the present consumables. A standard ESAB LAH 500 constant power source was used for continuous wire welding. Welding was done in a water cooled jig in accordance with British Standard of BS 6693: 1988 Part 5 [Mirza et al. (1999) and Mirza et al. (2013)].
Solid and metal cored wires results is reported that, an increase in CO\textsubscript{2} had a marked effect on diffusible hydrogen and, for both consumables, the weld hydrogen content decreased as the CO\textsubscript{2} content increased in the Ar–CO\textsubscript{2} mixtures. For both consumables, the diffusible hydrogen content was approximately the same with Ar–2%O\textsubscript{2} as with pure argon gas; as the CO\textsubscript{2} content of the shielding gas increased, the weld bead convexity increased and the depth of penetration increased [Mirza et al. (1999) and Mirza et al. (2013)].

The use of Ar–CO\textsubscript{2} mixtures with lower proportions of CO\textsubscript{2} improves the recovery of alloying elements, reduces weld metal oxygen levels, and increases the yield and ultimate tensile strength of the weld. The effects of varying the proportions of CO\textsubscript{2} in Ar–CO\textsubscript{2} mixtures on operating characteristics and mechanical properties have also been reported for other types of cored wire consumables. The Charpy impact transition temperature, for example, increased or decreased depending on the wire type. The CO\textsubscript{2} content is increased progressively towards 100%, increased penetration, higher spatter, a more convex bead, a tendency for globular arc transfer, and a reduction in mechanical properties of the weld result. Sometimes Ar–O\textsubscript{2} gas mixtures are used, as the addition of 2%O\textsubscript{2} to argon gas provides an oxidising atmosphere approximately equivalent to 5%CO\textsubscript{2} in argon and promotes the same operational characteristics as the Ar–CO\textsubscript{2} gas mixture [Mirza et al. (1999) and Mirza et al. (2013)].

The results for each shielding gas showed that the addition of CO\textsubscript{2} had a significant effect on the hydrogen emission peak, tending to cause a flattening of the peak and attenuation of the signal. This result was attributed to the two separate simultaneously occurring phenomena: (i) the absorption of hydrogen emissions by CO molecules which were present in the outer regions of the plasma (ii) the absorption of the hydrogen emissions by nonexcited hydrogen atoms which were also present in the outer regions of the arc plasma. Higher CO\textsubscript{2} contents were used and no secondary additions of hydrogen were made to the arc which could affect the arc characteristics. CO\textsubscript{2}, present in the arc plasma, tends to displace hydrogen from the hotter regions of the arc where hydrogen absorption is greatest, thereby increasing the hydrogen content of the outer (cooler) regions of the arc plasma [Mirza et al. (1999) and Mirza et al. (2013)].

A decrease in hydrogen content for a metal cored wire when welding under dip mode using an Ar–20%CO\textsubscript{2} shielding gas. The welding arc is sustained by the flow of current in an ionised
gas. The ease of ionization of the gas, therefore, will influence the ability to initiate and maintain the arc. The ease of ionisation is indicated by the ionisation potential of the gas; as the argon atoms are readily ionised at the arc, a highly charged path between the electrode and the work piece results. This concentration of energy constricts the droplet size of the molten metal, thus keeping transfer well within the spray mode. The heat input for CO₂ is slightly higher than for argon or Ar–CO₂ mixtures. This results in a hotter arc with increased fusion and a coarse microstructure [Mirza et al. (1999) and Mirza et al. (2013)].

With CO₂ shielding, molten metal at the tip of the wire is transferred as globules which are larger than the diameter of the electrode. Before detachment, the molten metal is held on to the electrode by surface tension. The time of suspension depends on the density of the metal: the lower the density of the metal, the larger the globule that can be formed before the globule falls. When enough metal is melted, gravity forces on the liquid and the magnetic pinch effect cause a section adjacent to the liquid interface to form a neck [Mirza et al. (1999) and Mirza et al. (2013)]. Gas metal reactions involving carbon, oxygen, silicon, and manganese in CO₂ welding, also calculated a mean effective reaction temperature of 2300°C, stating that intense reactions occurred in the region of the arc roots where thermodynamic equilibrium was achieved. The results of their investigation suggested that oxygen absorption occurred through the saturation of the surface layers of the molten metal at the weld pool, electrode tip, and transferring droplets. The extent of absorption is governed by the temperature and transport processes removing the saturated surface metal and replacing it with other metal, which in turn becomes saturated.

Flux cored wire, with CO₂ shielding; lower weld hydrogen levels were obtained than with the Ar–CO₂ mixture. It was also observed that, for both shielding gases, higher weld hydrogen contents were obtained with increasing welding current and voltage, and decreasing electrode stick out. However, at lower voltages, the difference between weld hydrogen contents using the different shielding gases was not significant [Mirza et al. (1999) and Mirza et al. (2013)].

When cored and solid wires were used for welding with a range of shielding gases, with increasing CO₂ content, the amount of hydrogen recovered from the weld metal decreased. As the CO₂ content of the shielding gas increases, the droplet detaching from the wire during welding becomes more globular. The larger droplets absorb less hydrogen from the weld
atmosphere owing to the low surface area/volume ratio and, hence, less hydrogen enters the weld pool. Also, CO\textsubscript{2} produces a hotter arc, driving off hydrogen from the weld pool. With high welding voltage (34 V) and current, an Ar–20\%CO\textsubscript{2} shielding gas gave a weld hydrogen content of 10.36 mL/100g but, with 100\%CO\textsubscript{2}, this decreased to 6.05 mL/100g. With lower voltages and currents, bigger droplets are formed in any case, so increasing the CO\textsubscript{2} content in an Ar–CO\textsubscript{2} mixture makes no significant difference to the weld hydrogen content.

Metal temperatures during welding may range from that of molten metal down to that of unaffected base metal. A continuous temperature gradient will exist between the two extremes. The microstructure and mechanical properties of a portion of the heated steel (HAZ) will be changed as a result of welding. Such changes will depend upon the composition of the steel and the rate at which the steel is heated and cooled. With some steels, the thermal cycle may result in the formation of martensite in the weld metal and HAZ. The amount of martensite formed and the hardness of the steel depend upon the carbon content as well as the heating and cooling rate.

In Fig 2.10 gives relationship between hardness and carbon content for steels that are 50 or 100\% martensite after quenching. Martensite transformation and resulting high hardness can lead to cracking in the weld and HAZ if the metal cannot yield to relieve welding stresses. The degree of hardening in HAZ is an important consideration determining the weldability of a carbon steel. Obviously, weldability generally decreases with increasing carbon or martensite in the weld metal or HAZ or both.

![Fig 2.10 Relationship between carbon content and maximum hardness of steels with microstructures 50 and 100% martensite (Kou, 2002)](image-url)
Non-metallic inclusion

Normal sulphur and prosperous contents in carbon steels do not promote weld metal cracking. Large amounts of these elements are added to some steels to provide free machining characteristics. These free machining steels have relatively poor weldability because of hot tearing in the weld metal caused by low melting compounds of phosphorus and sulphur at the grain boundaries. The grains may be torn apart by thermal stresses during cooling. High sulphur content also promotes weld metal porosity.

Lead is also added for improve machinability it is nearly insoluble in steel and exists as district globules. The lead can melt during welding and volatilize into the weld fumes. Lead may, on occasion, cause porosity and embrittlement of steel. The major concern with the lead, however, is its presence in the welding fumes and toxicity. This requires special precaution to assure good ventilation during welding. Normally, free mechanism steels must be welded. If one of these steels must be welded, low hydrogen electrodes and low welding currents should be used to limits dilution, porosity and cracking.

Hydrogen

Carbon steel exhibit increasing susceptibility to hydrogen induced cracking with increasing carbon content greater than about 0.15%. However, steels with 0.15% carbon or less are not immune to this problem, especially when thick section is welded.

Weld cooling rate

When arc welding thick sections, the weld metal and HAZ can be hardened significantly as a result of quenching by the large mass of base metal. The cooling rate and the CE of steel are the controlling factors in determining the degree of hardening. The cooling rate depends primarily on the following factors.

a. The section thickness and joint geometry,
b. The base metal temperature before welding commences,
c. The rate of heat input.

Consequently, the use of higher welding current, slower welding speed high heat input, or pre heating of the base metal will reduce the cooling rate of the weld zone. Pre heat should be maintained during the welding of successive beads. With higher carbon content or increased section thickness, a higher pre heat and interpass temperature should be used to decrease the weld cooling rate and thus control the weld hardness and minimize the likelihood of cracking.
**Mild Steel**

Carbon steels containing from about 0.15 to 0.30% carbon are commonly called mild steels. Underbead cracking or lack of toughness in the HAZ is not usually encountered when welding mild steels containing no more than 0.20% carbon and 1% Mn, such steels can be welded without preheat, post heat, or special welding procedures when the joint thickness is less than 1in., and joint restraint is not severe.

As the carbon and Mn contents increase to about 0.30 and 1.40% respectively, weldability of the steels remains good, but the welds are susceptible to underbead cracking because of increased hardenability and strength. Welding with low H₂ process is recommended. Preheating and control interpass temperature may be required; particularly when the joint thickness is greater than 1 in. or joint restraint is high. If the H₂ induced cracking still is problem with these procedures H₂ may be diffused from the joint using a postweld thermal treatment.

Some mild steels are supplied in the normalized or quenched and tempered condition to provide good toughness or high strength properties. Tensile strengths may range from 65 to 100ksi, depending upon the carbon and Mn content and heat treatment.

The welding procedures for heat treated mild steels are guided to a larger extent by a need to have the weld metal, the HAZ, and unaffected base metal possess about the same toughness. Precautions should be taken to ensure that welding is done using low H₂ conditions. In general, heat treated mild steels are arc welded without preheat, but preheat should be used when the metal temperature is below about 50°F. In fact, preheat of about 100° F or higher should be used if the plate thickness is over 1in. or the joint is highly restrained.

Dilution must be considered when selecting a filler metal to provide specified joint mechanical properties in selected steel. Mechanical properties for weld metal given in filler metal trade literature are for undiluted material. The properties of weld metal in an actual fabrication may differ from the reported values because of dilution effects. For heat treated mild steels, low alloys steel filler metal may be required to meet mechanical property requirements. However, the weld metal strength should not greatly exceed the strength of the base metal. High strength weld metal may require softer HAZ to undergo a relatively large amount of strain when the joint is subjected to deformation near room temperature. Under such conditions, fracture may occur prematurely in the HAZ because of excessive localized strain. In butt joint, the filler metal should be selected to provide weld metal with essentially the same strength as the base metal.
For fillet welds, a filler metal of lower strength is sometimes used to provide sufficient ductility to accommodate stress concentrations. However, a low strength filler metal should not be used in discriminately as a remedy for cracking difficulties.

### 2.3.4 Microstructures

**Microstructures of Weld Metal**

Several continuous cooling transformation (CCT) diagrams have been sketched schematically to explain the development of the weld metal microstructure of low carbon and low-alloy steels. Figure 2.11 shows CCT diagram for weld metal of low carbon steel. The hexagons represent the transverse cross sections of columnar austenite grains in the weld metal. As austenite (γ) cooled down from high temperature, ferrite (α) nucleates at the grain boundary of austenite grains and grows inward. The grain boundary ferrite is also called “allotriomorphic” ferrite without a regular faceted shape reflecting its internal crystalline structure. At low temperature, mobility of the planer growth front of the grain boundary ferrite decreases and Widmanstatten ferrite, also called side-plate ferrite, forms instead. These side plates can grow faster because carbon, instead of piling up at the planar growth front, is pushed to the sides of the growing tips. Substitutional atoms do not diffuse during the growth of Widmanstatten ferrite. At even low temperature it is too slow for Widmanstatten ferrite to grow to the grain interior and it is faster if new ferrite nucleates ahead of the growing ferrite. This new ferrite, that is, “acicular ferrite”, nucleates at inclusion particles and has randomly oriented short ferrite needles with basket weave feature.

![Continuous-cooling transformation diagram for weld metal of low carbon steel](Kou, 2002)
Acicular ferrite and bainite are considered to be formed by the same transformation mechanism. Both microstructures developed in the same range of temperature below the high temperature where allotriomorphic ferrite or peralite form, but above martensitic start temperature. In bainite, the ferrite initiates at the austenite grain boundary, whereas acicular ferrite is nucleates intragranularly at non-metallic inclusions. Most of work on acicular ferrite has been carried out in welds (Bhadeshia, 2001). The high density of inclusions present in steel weld deposits ensures a high density of nucleation sites, which favours the development of an acicular ferrite microstructure instead of a bainitic one.

The nature of acicular ferrite phase has been cause of much research. In fact, the form “acicular ferrite” is a misnomer. In two dimensions, acicular ferrite appears as “randomly” oriented, needle-shaped particles, but this belies its true morphology, which is that of a thin, lenticular plate. For a typical low alloy C-Mn steel weldment, acicular ferrite begins to appear during cooling in the range of 500 °C to 440 °C, a temperature range which is consistent with the observation of plate morphologies of ferrite in wrought steels.

It is well established that acicular ferrite nucleates at nonmetallic inclusions which occurs frequently in arc welds. With respect of the carbon concentration of acicular ferrite during transformation, experiments and thermodynamic theory demonstrated that the growth of acicular ferrite is diffusionless, the ferrite inheriting the chemical composition of the parent austenite. However, immediately after transformation, the excess carbon in the acicular ferrite is rejected into residual austenite. Latter process can occurs in a matter of seconds (Bhadeshia, 1969). Mechanism of transition from bainite to acicular ferrite has been studied by Bhadeshia, 1991. Some of the experimental results which confirm that acicular ferrite is nothing but intragranularly nucleated bainite are summarized schematically in figure 2.12. The transformation temperatures are identical for all the cases illustrated, the differences being that

Figure 2.12 Inclusion density changed for the same austenite grain size- the sample with the smaller inclusion density transforms to bainite since the relative number density of austenite grain boundary nucleation sites is large.

Figure 2.12 An increase in the austenite grain size at constant inclusion density stimulates a transition from a predominately bainitic to an acicular ferrite microstructure.
Figure 2.12 the growth layer of inert allotriomorphic ferrite at the austenite grain surface causes a transition from bainite to acicular ferrite.

Factors affecting microstructure

The effect of several factors on the development of microstructure of the weld metal was studied by Bhadeshia and Suensson (Bhadeshia, 1969), as shown in figure 2.13 vertical arrows indicates the direction in which these factors increase in strength. This will further explain with help of CCT curves.

Factors

The weld metal composition,
The cooling time from 800 to 500 °C,
The weld metal oxygen content and
Austenite grain size

Cooling time

Consider the left CCT curves (broken line) in figure 2.13. As cooling slow down (Δt_{8-5} increase ) from curve 1 to curve 2 and curve 3 and the transformation product can change from predominately bainite (figure 2.13), to predominately acicular ferrite (2.13) to predominately grain boundary and widmanstatten ferrite (figure 2.13)

![CCT Curves](image)

Figure 2.13 Schematic showing effect of alloy addition, cooling time from 800 to 500°C, weld oxygen content and austenite grain size (Kou, 2002)

Alloying addition

An increase in alloying addition (higher hardenability) will shift the CCT curves toward longer times and lower temperatures. Figure 2.48 shows effect of alloying elements, grain size and oxygen on CCT diagram for weld metal of low carbon steel. The transformation product can change from predominately grain boundary and widmanstatten ferrite (left CCT curve) to predominately acicular ferrite (middle CCT curves) to predominately bainite (right CCT curves), as show in figure 2.48.
Figure 2.48: Effect of alloying elements, grain size and oxygen on CCT diagram for weld metal of low carbon steel (Kou, 2002)

**Grain size**

Similar to the effect of alloying additions, an increase in austenite grain size (less grain boundary area for ferrite nucleation) will also shift the CCT curve toward longer time and lower temperatures.

**Weld metal oxygen content**

The effect of the weld metal oxygen content on the weld metal microstructure is explained as follows, increasing the weld metal oxygen content increased the inclusion volume fraction and decreased the average inclusion size. Fine second phase particles are known to increasingly inhibit grain growth by pinning the grain boundaries as the particles get smaller and more abundant.

Large inclusions, which are favored by lower oxygen weld metal oxygen content, can act as favorable nucleation sites for acicular ferrite. Appropriate inclusions appear to be in the size range 0.2-2.0μm, the mean size of about 0.4μm has been suggested to be optimum value. On other hand, many small oxide inclusion (<0.2μm) can be generated if the oxygen content is too high (>300ppm). These inclusions, though small to be effective nuclei for acicular ferrite, reduces the grain size and thus provide much smaller grain boundary area for nucleation of grain boundary ferrite.
In GMAW with oxygen or carbon dioxide added to argon, as shown in figure 2.49. With Ar-O₂ and Ar-CO₂ as the shielding gas, it becomes the volume percentage of CO₂ and O₂ in the shielding gas that will produce the oxygen content in the weld metal. Author has reported that higher the shielding gas oxygen equivalents, more hardenability elements such as Mn and Si from the filler wire were oxidized. Again cooling curve 3 in figure 2.48 have to consider. As the shielding gas oxygen equivalent is reduced, the CCT curves can shift from left (broken lines) middle (solid lines) and a predominately acicular ferrite microstructure is produced. If the shielding gas oxygen equivalent is reduced further, the CCT curves can shift from middle (solid line) to right (dotted line) and acicular ferrite no longer predominates.

![Diagram](image)

Figure 2.49: Acicular ferrite content as a function of shielding gas oxygen equivalent for gas metal arc welds (Kou, 2002)

### 2.3.5. Specification for pressure vessel plate, carbon steel, for moderate and lower temperature services

This specification covers carbon steel plates intended primarily for service in welded pressure vessels where improved notch toughness is important. Plates under this specification are available in four grades having different strength levels as shown in Table 2.4.
Table 2.4 Carbon steel mechanical properties

<table>
<thead>
<tr>
<th>Grade</th>
<th>Tensile Strength, ksi [MPa]</th>
<th>Yield Strength</th>
<th>Elongation in 8in.[200mm],min %</th>
<th>Elongation in 2in.[50mm],min %</th>
</tr>
</thead>
</table>

The maximum thickness of plates is limited only by the capacity of the composition to meet the specified mechanical property requirements; however, current practice normally limits the maximum thickness of plates furnished under this specification as shown in Table 2.5.

Table 2.5 Limitation of max and min thickness

<table>
<thead>
<tr>
<th>Grade</th>
<th>Max. Thickness, in,(mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>55 [380]</td>
<td>12 [305]</td>
</tr>
<tr>
<td>60 [415]</td>
<td>8 [205]</td>
</tr>
<tr>
<td>65 [450]</td>
<td>8 [205]</td>
</tr>
<tr>
<td>70 [485]</td>
<td>8 [205]</td>
</tr>
</tbody>
</table>

The values stated in either inch-pound units or SI units are to be regarded separately as standard. Within the text, the SI units are shown in brackets. The values stated in each system are not exact equivalents; therefore, each system must be used independently of the other. Combining values from the two systems may result in non conformance with the specification [https://masteel.co.uk/pressure-vessel-steel/].