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A Study on Effect of Various Process Variables in Gas Metal Arc Welding

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Abstract: Gas metal arc welding (GMAW) is currently the most widely used arc welding process. It had its beginning in the late 1940s and was developed to make welding a faster, more profitable process. Benefits such as high production rates, high weld quality, ease of automation, and the ability to weld many metals make it attractive to manufacturers. This paper presents a study on effect of various process variables in GMAW.

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I. INTRODUCTION

GMAW is a process that joins metals together by heating them with an electric arc that is established between a consumable electrode (wire) and the workpiece. An externally supplied gas or gas mixture acts to shield the arc and molten weld pool.

GMAW is sometimes referred to by its subtypes metal inert gas (MIG) welding or metal active gas (MAG) welding. It was primarily developed as a high current density, small diameter metal electrode process with argon shielding for aluminium, hence the term MIG was appropriate. But when it was extended to the welding of ferrous and nonferrous metals, addition of 1-2 % oxygen to argon was found necessary to get smooth metal transfer. Later it was established that mild steel could be welded using 100 % carbon dioxide or argon-carbon dioxide mixture as a shielding gas. Since these gases are not inert, the process came to be termed as MIG/CO_2 or MIG/MAG welding process. MAG is an abbreviation of metal active gas in which active gas refers to argon-oxygen, carbon dioxide and argon-carbon dioxide mixture, which are chemically reactive and not inert. The *American Welding Society* refers to the process as Gas Metal Arc Welding and has given it the letter designation GMAW. This term appears simpler; it covers inert as well as active shielding gas.

GMAW can be done in three different ways:

1. **1.** Semiautomatic welding – equipment controls only the electrode wire feeding. Movement of welding gun is controlled by hand. This may be called hand-held welding.
2. **2.** Machine welding – uses a gun that is connected to a manipulator of some kind (not hand-held). An operator has to constantly set and adjust controls that move the manipulator.
3. **3.** Automatic welding – uses equipment which welds without the constant adjusting of controls by a welder. On some equipment, automatic sensing devices control the correct gun alignment in a weld joint.

II. PRINCIPLE OF GMAW

This process uses an electric arc as a source of heat to melt and join the metals. An arc is an electrical discharge over a gaseous path between two electrodes which takes place through an electrically conducting hot ionized gas known as plasma (Fig. 1).

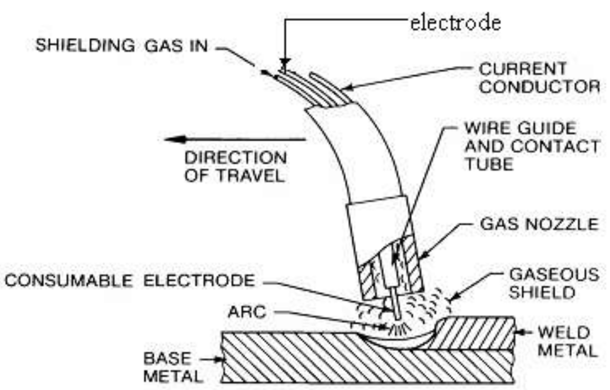

Figure 1: Principle of GMAW [1]

Electric arc is established between the workpiece and the consumable bare wire electrode which is fed through a welding gun. The heat of the arc melts the surface of the base metal and the end of the electrode. The electrode serves to carry the current and sustain the electric arc between its tip and workpiece and continuously melts the wire as it is fed to the weld puddle. This also supplies filler metal to the joint. The arc and the molten puddle are protected from contamination by the atmosphere (i.e. oxygen and nitrogen) with an externally supplied gaseous shield of gas – either inert such as argon, helium or an argon-helium mixture, or active such as carbon dioxide, argon-carbon dioxide mixture. These gases are delivered through the welding gun and cable assembly.

III. GMAW OPERATIONS

The basic technique for GMAW is quite simple, as it is usually carried out with a hand-held gun as a semiautomatic process. Before beginning to weld, the welding station should be checked for safety. All electrical, gas, and water connections must be checked for tightness. Adequate fixturing and clamping of the work are required with adequate accessibility for the welding gun. When complete joint penetration is required, some method of weld backing helps to control it. A backing strip, backing weld, or copper backing bar can be used. Backing strips and backing welds usually are left in place. Copper backing bars are removable. The assembly of the welding equipment should be done according to the manufacturer's directions.

GMAW requires the operator to guide the welding gun with proper position and orientation along the area being welded. Keeping a consistent contact tip-to-work distance and electrode extension is important, because a long stick-out distance can cause the electrode to overheat and will also waste shielding gas. Stick-out distance varies for different GMAW weld processes and applications. For short circuit transfer, the stick-out is generally $^{1}/_{4}$-$^{1}/_{2}$ ", for spray transfer the stick-out is generally $^{1}/_{2}$ ". The position of the end of the contact tip to the gas nozzle is related to the stick-out distance and also varies with transfer type and application. The gun nozzle size and the shielding gas flow rate should be set according to the recommended welding procedure for the material and joint design to be welded. The gun contact tube and electrode feed drive rolls are selected for the particular electrode composition and diameter, as specified by the equipment manufacturer. The electrode feed rate and welding voltage are set to the recommended values for the electrode size and material. With a CV power source, the welding current is established by the electrode feed rate. Other variables, such as slope control, inductance, or both, should be adjusted to give good arc starting and smooth arc operation with minimum spatter. The optimum settings will depend on the equipment design and controls, electrode material and size, shielding gas, weld joint design, base metal composition and thickness, welding position, and welding speed.

To start welding, tilt the top of the gun 5°-15° in the direction of travel. To start the arc, the wire feeder and the gas, squeeze the trigger on the gun. The wire starts arcing as soon as it feeds out far enough to touch the metal. As the weld pool reaches the proper width, which occurs rapidly, move the welding gun forward. Watching the width of the weld pool to maintain a uniform size, continue this procedure until the end of the weld is reached. More than one pass may be required to fill a weld groove. Each pass should be cleaned before the next pass is laid [2].

Modes of Metal Transfer

In GMAW, metal is transferred in the form of molten liquid droplets to the workpiece. Depending on the welding conditions, metal transfer can take place in three principal modes: short circuit, globular, and spray (Fig. 2).

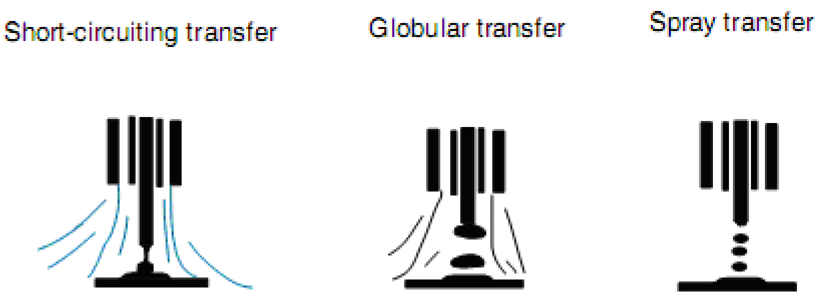

Figure 2: Metal transfer modes in GMAW [3]

Short circuit transfer refers to the welding wire actually "short circuiting" (touching) the base metal between 90-200 times/sec. The electrode touches the workpiece and creates a short circuit, which momentarily extinguishes the arc. The power supply senses the electrical resistance and increases current sufficiently to melt the end of the electrode and reignite the arc. The short circuit metal transfer occurs at low voltage and moderate welding current, and is characterized by periodic contact of the drop with the melting pool, causing instability in the welding voltage and

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current; this may present intense formation of spatters [4]. Since there is no arc established during the short circuit, the overall heat input is low, and the depth of fusion is relatively shallow. Because of its low heat input characteristics, the process produces small, fast-freezing weld puddles, which makes it suitable for welding in all positions. It is commonly used in welding thin sheets.

Globular transfer refers to the state of transfer between short circuiting and spray arc transfer. Large globules of wire are expelled off the end of the electrode wire and enter the weld puddle. Globular transfer takes place when current and arc voltages are between the short circuiting and spray transfer range. During welding, the melting metal globule at the tip of the wire grows as time passes, until it detaches under the effect of gravity. This causes a deposition of large drops, much larger than the wire diameter, in the melting pool, causing spatters [4]. Globular transfer is characterized by a drop size 2-4 times the diameter of the electrode. It is not effective for GMAW.

Spray arc transfer "sprays" a stream of tiny molten droplets across the arc, from the electrode wire to the base metal. The spray transfer mode occurs with high voltage and current, above a stripe named transition current (current stripe between globular and spray mode). The drops are small, close to the wire diameter size, which are thrown at high frequency into the melting pool. This mode presents good process stability, and a good aspect of the weld bead with very few spatters. It is widely used in welding thick steel plates and aluminium parts [4].

Spray transfer is achieved at high current for constant current GMAW, which results in a thermal load too high to apply to thin sectioned or heat sensitive materials, thereby its application is restricted. In an effort to overcome this difficulty, pulsed current GMAW was introduced. In GMAW-P, the welding current is alternatively and periodically varied between background (base) and peak (pulse) values.

IV. PROCESS VARIABLES

The GMAW parameters are the most important factors affecting the quality, productivity and cost of welding joint. Knowledge and control of these variables is essential to consistently produce welds of satisfactory quality. These variables are not completely independent, and changing one generally requires changing one or more of the others to produce the desired results. Considerable skill and experience are needed to select optimum settings for each application. The optimum values are affected by type of base metal, electrode composition, welding position, and quality requirements. There is no single set of parameters that gives optimum results in every case. The following are some of the variables that affect weld penetration, bead geometry and overall weld quality.

4.1 Welding Current

The process requires sufficient electric current to melt both the electrode and a proper amount of base metal. Current is set indirectly by the wire feed speed and diameter. It is the main parameter for welding and has to be chosen according to plate thickness and welding speed with respect to the weld quality. When all other variables are held constant, the welding amperage varies with electrode feed speed or melting rate in a nonlinear relation, if a CV power source is used (Fig. 3). At low current levels for each electrode size, the curve is nearly linear. However, at higher welding currents, particularly with small diameter electrodes, the curves become nonlinear, progressively increasing at a higher rate as welding amperage increases. This is attributed to resistance heating of the electrode extension beyond the contact tube. The curves can be approximately represented by the equation $WFS = aI + bLI^2$, where

WFS = the electrode feed speed, mm/s,
a = a constant of proportionality for anode or cathode heating. Its magnitude is dependent upon polarity, composition, and other factors, mm/(s.A),
I = the welding current, A,
b = constant of proportionality for electrical resistance heating, $s^{-1}.A^{-2}$,
L = the electrode extension or stick-out, mm.

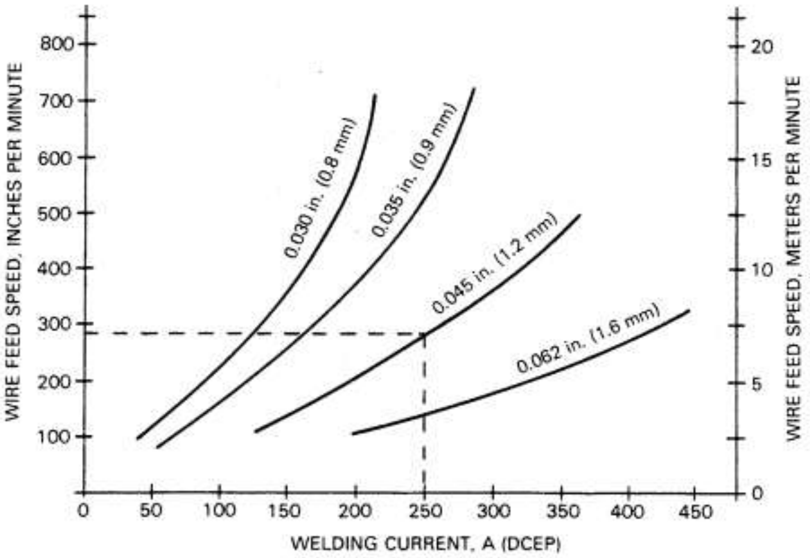


Figure 3: Typical currents v/s feed speeds for carbon steel electrodes [1]

As shown in the figure, when the diameter of the electrode is increased (while maintaining the same electrode feed speed), a higher welding current is required. The relationship between the electrode feed speed and the welding current is affected by the electrode chemical composition. Using too high amperage may cause problems such as excessive spatter, electrode overheating and cracking. It also affects metal transfer. With all other variables held constant, an increase in welding current (electrode feed speed) results in the following:

1. An increase in the depth and width of the weld penetration.
2. An increase in the deposition rate.
3. An increase in the size of the weld bead.

4.2 Polarity

The term polarity is used to describe the electrical connection of the welding gun with relation to the terminals of a DC power source. DC electrode positive (DCEP) gives stable electric arc, low spatter, good weld bead geometry and the greatest penetration depth (Fig. 4) [2]. DC electrode negative (DCEN) polarity is usually limited to globular transfer, and it is seldom used because the resulting arc is unsteady and has an unacceptable spattering level. Most problems inherent to the DCEN are due to the strong repulsive force that acts under the droplet at the electrode wire tip (cathode). Since the electron flow is from the electrode wire toward the workpiece, repulsive force acting under the droplet appears due to electron emission, generating an erratic cathodic root and therefore an asymmetrically repelled droplet [60].

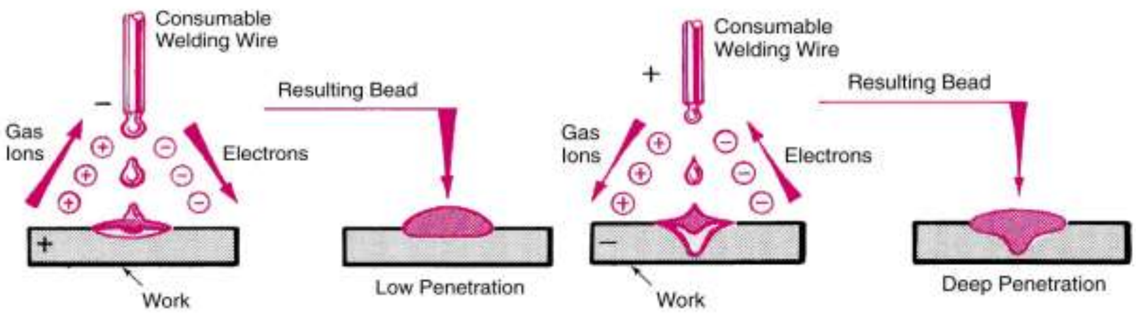


Figure 4: Effect of polarity [5]

4.3 Arc Voltage (Arc Length)

Arc voltage is the voltage measured between the tip of the unmelted electrode wire and the surface of the weld puddle. Arc voltage is directly related to arc length. Arc length refers to the distance from the molten tip of the electrode core to the molten weld pool (Fig. 5). Increasing the voltage increases the arc length. Higher voltages will cause the bead to be wider and flatter. Excessively high voltage may cause porosity, spatter and undercut. Reduction in voltage results in a narrower weld bead with a higher crown and deeper penetration. Excessively low voltage may cause stubbing of the electrode [6].

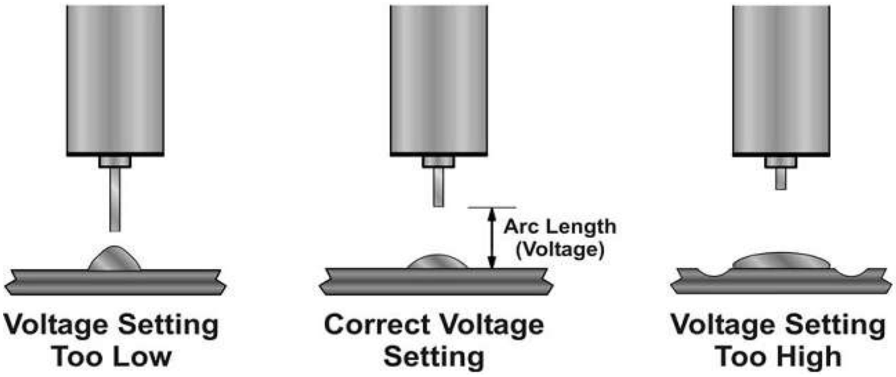


Figure 5: Voltage – bead changes

Arc voltage settings vary depending on the material welded, current, shielding gas, metal thickness, type of joint, welding position, electrode size and mode of metal transfer. Short arc welding requires relatively low voltages while spray arc requires higher voltages. As welding current and wire burn-off are increased, the welding voltage must also be increased somewhat to maintain stability. Trial runs are necessary to adjust the arc voltage to produce the most favorable arc characteristics and weld bead appearance [6].

4.4 Travel Speed

Travel speed is the linear rate at which the arc is moved along the weld joint. It is measured in inches/min or mm/sec. With all other conditions held constant, weld penetration is maximum at an intermediate travel speed [7]. It has a direct influence on bead shape, depth of fusion and heat input into the base metal.

When the travel speed is decreased, the filler metal deposition per unit length increases (Fig. 6). Extremely low speeds may result in reduction of effective penetration, as the welding arc impinges on thick layer of the molten metal and weld puddle rolls ahead of the arc. A wide weld bead is also a result of low speed [6].

As the travel speed is increased, the thermal energy per unit length of weld transmitted to the base metal from the arc is at first increased, because the arc acts more directly on the base metal. With further increase in travel speed, less thermal energy per unit length of weld is imparted to the base metal. Therefore, melting of the base metal first increases and then decreases with increasing travel speed [1]. But further increase in speed decreases penetration and can cause undercut due to insufficient material to fill the cavity produced by the arc [3].

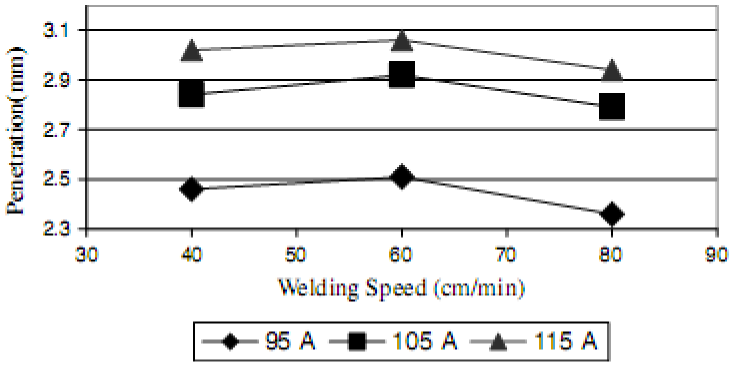


Figure 6: Penetration v/s welding speed [8]

Faster travel speeds produce narrower beads that have less penetration. This can be an advantage for sheet metal welding where small beads and minimum penetration are required. Travel speed also affects heat input, which in turn influences the metallurgical structure of the weld metal. The cooling rate varies proportionately with the travel speed. Also, the heat affected zone increases in size as the cooling rate decreases. As the material thickness increases, the travel speed must be lowered.

4.5 Electrode Extension

Electrode extension is the distance between the end of the contact tube and the end of the electrode (Fig. 7). The popular non-standard term is electrical stick-out (ESO). It is an important welding parameter for controlling the deposition rate and the bead geometry. An increase in the electrode extension results in an increase in electrical resistance of electrode, causing it to be heated, known as I^2R heating [9]. This leads to lower requirement of current at any given wire feed rate. Too long stick-out results in excess weld metal being deposited with low arc heat which leads to poor weld bead shape and shallow penetration. Arc stability is also affected. Too short stick-out may cause burn-back resulting in damage to the contact tube, excessive arc length and even interruption in the process. The desirable electrode extension is generally 5-15 mm for short circuiting transfer and 13-25 mm for other types of metal transfer.

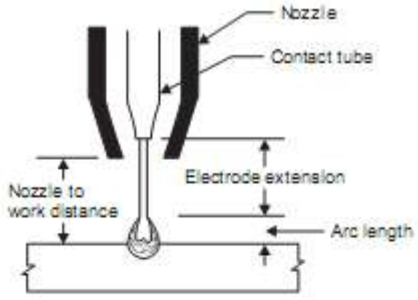


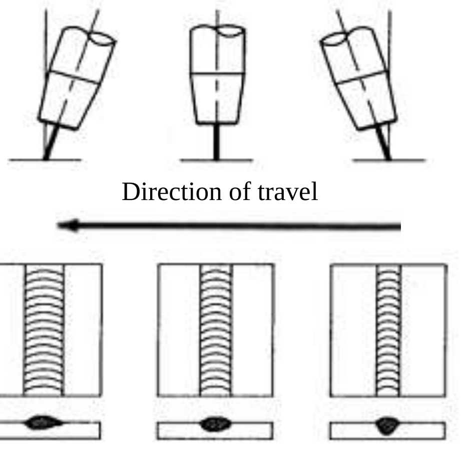
Figure 7: Electrode extension [10]

Nozzle-to-work distance (NWD) also has an influence in controlling the bead shape and quality. Too short a NWD results in damage to the gas nozzle by excessive heating, while too long a NWD affects the shielding gas efficiency. This should be about 1-1.5 times inner diameter of the gas nozzle being used [9].

4.6 Electrode Orientation

The orientation of the welding electrode with respect to the weld joint affects the weld bead shape and penetration. The electrode orientation is described in two ways: (i) by the relationship of the electrode axis with respect to the direction of travel (travel angle), and (ii) the angle between the electrode axis and the adjacent work surface (work angle). When the electrode points opposite to the direction of travel, the technique is called backhand welding with a drag angle. When the electrode points in the direction of travel, the technique is forehand welding with a lead angle. The electrode orientation and its effect on the width and penetration of the weld are illustrated in Fig. 8. Backhand welding with drag angle produces a weld with deep penetration, more stable and higher buildup. Forehand welding with lead angle produces a weld with shallow penetration and light buildup [11].

For all positions, the electrode travel angle normally used is a 5°-15° drag angle for good control and shielding of the molten weld pool. When producing fillet welds in the horizontal position, the electrode should be positioned about 45° to the vertical member (work angle) (Fig. 9) [7]. There are some distinct advantages of a push technique. One advantage is when relatively thin materials are to be welded, or when doing hard-facing. Low penetration would be required, and a push technique along with a faster travel speed can help achieve this in certain applications.



Forehand technique   Perpendicular technique   Backhand technique

Figure 8: Effect of electrode orientation [2]

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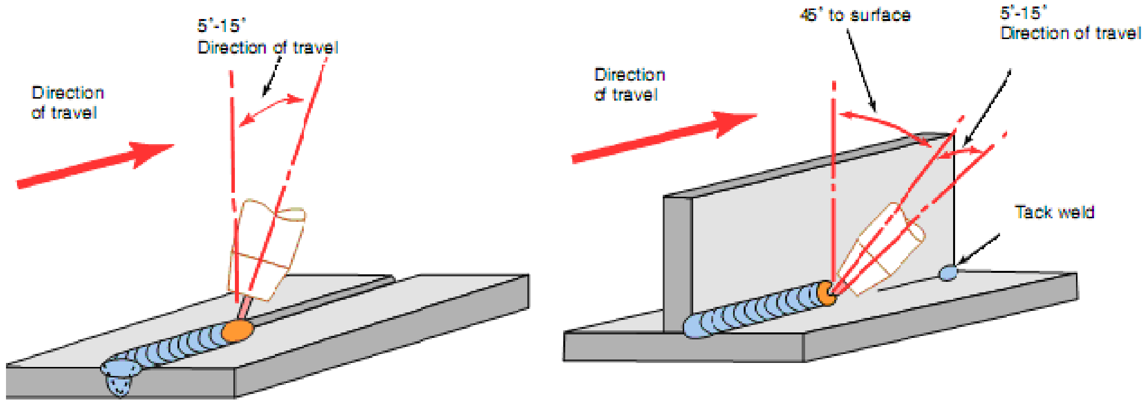

(a) V-groove weld on a butt joint in the flat welding position

(b) Fillet weld on a T-joint in the horizontal welding position

Figure 9: Effect of electrode position and welding technique [7]

4.7 Electrode Size

Each electrode wire size has a workable limit within which it can be effectively used. It affects penetration and weld width in that for the same current lower diameter wire gives deeper penetration, while wider beads with shallow penetration are obtained with bigger diameter wires (Fig. 10) [9].

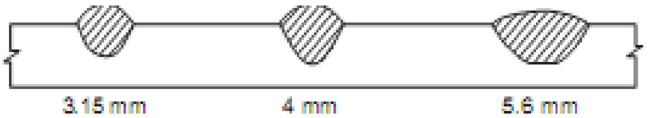

Figure 10: Effect of electrode size on bead geometry [10]

Electrode diameter also indirectly helps to set the welding current. Welding current lower than the optimal range results in lack of fusion, while higher current results in increasing spatter, porosity and poor bead appearance (Fig. 11).

Figure 11: Welding spatter

4.8 Shielding Gas

Shielding gas is required to protect the weld pool and molten droplet transferred across the arc. In addition, it should promote a stable arc, desired mode of metal transfer and weld bead characteristics. Each shielding gas has its own properties, including ionization potential, and produces unique arc characteristics. Traditionally, CO_2 has been used as a shielding gas due to its cheapness, but its use has been limited to steels because of the problem of spatter, oxidation losses and poor all-position performance [3].

Inert gases such as Ar and He provide the necessary shielding because they do not form compounds with any other substance and are insoluble in molten metal. However, when used as pure gases for welding ferrous metals, they may produce an erratic arc action, promote undercutting, and result in other flaws. Therefore, it is usually necessary to add controlled quantities of reactive gases to achieve good arc action and metal transfer with these gases. Adding O_2 or CO_2 to the inert gas tends to stabilize the arc, promote favorable metal transfer, and minimize spatter. As a result, the penetration pattern is improved and undercutting is reduced or eliminated [11].

High penetration level can be achieved by employing the shielding mixture of CO_2 and O_2 for joining low carbon and low alloy steels compared with traditional mixtures based on Ar [12]. In case of aluminium alloys penetration can be improved by adding 70-80 % He to Ar [9].

V. ADVANTAGES OF GMAW

The GMAW process enjoys widespread use because of its ability to provide high quality welds for a wide range of ferrous and nonferrous alloys at a low price. It has the following advantages:

1. Because of continuously fed electrode, it is much faster as compared to TIG or stick electrode welding.
2. Large metal deposition rates are achieved.
3. The ability to join a wide range of material types and thicknesses.
4. All-position welding capability.

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5. No flux is used. It produces smooth, neat, clean and spatter-free welded surfaces which require no further cleaning. This helps reducing total welding cost.
6. It can produce joints with deep penetration, which may permit the use of smaller sized fillet welds.
7. Less operator skill is required than in other conventional processes, because the arc length is maintained constant with reasonable variations in the distance between the contact tip and the workpiece.
8. Reduced welding fume generation.
9. It is easily adapted for high speed robotic, hard automation and semiautomatic welding applications.

VI. LIMITATIONS OF GMAW

Though highly versatile and useful, the process suffers from several drawbacks, namely:

1. It is slightly more complex as compared to TIG or stick electrode welding because a number of welding parameters, like electrode stick out, torch angle, type and size of electrode, welding torch manipulation, etc., are required to be controlled effectively to achieve good results.
2. Welding equipment is more complex, more costly and less portable.
3. It is more difficult to use in hard-to-reach places because the welding gun is larger than a shielded melt arc electrode. The welding gun must be 10-20 mm close to the joint to ensure that the weld metal is properly shielded.
4. The welding arc must be protected against air drafts that will disperse the shielding gas. This limits outdoor applications unless protective shields are placed around the welding area.
5. Because the process produces relatively high levels of radiated light, heat and arc intensity, some operators may find it uncomfortable, especially in confined areas.

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