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A Study on Metal Transfer Mechanism in Gas Metal Arc Welding

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ABSTRACT

Gas metal arc welding is currently the most widely used arc welding process, having overcome the old faithful "stick" welding, SMAW. It 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. All commercially important metals, such as carbon steel, high-strength low-alloy steel, stainless steel, aluminium, copper, and nickel alloys can be welded in all positions. A typical application is welding of aluminium bus bars in electrical industry and welding of sheet metal assembly. Gas metal arc welding process has become more popular in weld cladding than other processes due to its numerous advantages.
Keywords: Gas Metal Arc Welding, SMAW, SFBT, PIT, STT, CMT, DCEP, DCEN

I. INTRODUCTION

During gas metal arc welding, the electrode is melted and liquid droplets are formed at the tip of the electrode. The melted metal grows and is detached from the electrode (Fig. 1). This process of metal transfer includes droplet formation, detachment, and transfer in the arc. It plays an important role in determining the process stability, weld quality and productivity of welding. To understand molten metal transfer in arc welding requires understanding of the physics involved, even though the precise physics is not yet completely known. This should not come as a great surprise since arcs are small, their temperatures are high, and the dynamics of molten metal transfer are complicated [1]. The characteristics of the process are best described by the manner in which metal is transferred from the consumable wire to the workpiece.

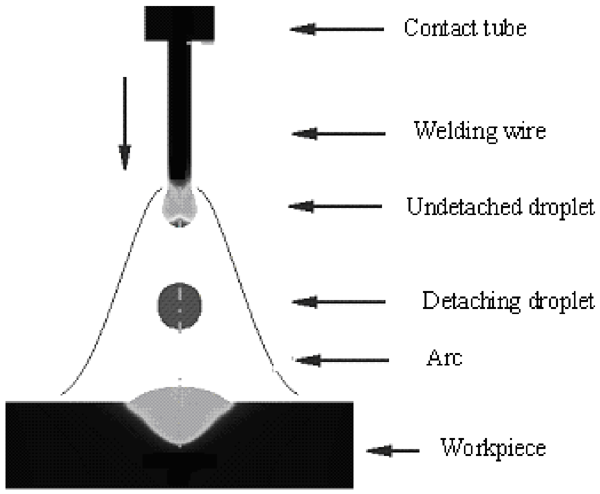


Figure 1: Metal transfer process in GMAW [2]

II. Literature Review

During welding process various forces act on the liquid droplet and also on the weld pool. These forces influence the mode of the metal transfer and the motion of the liquid metal in the droplet and the weld pool, which in turn can have an effect on process stability, weld penetration, and bead shape. The forces controlling this transfer are very complex, and together with the size of droplets, they determine the mechanisms of metal transfer. These forces affecting metal transfer are gravity, surface tension, electromagnetic force, plasma drag force and force due to arc pressure (Fig. 2).

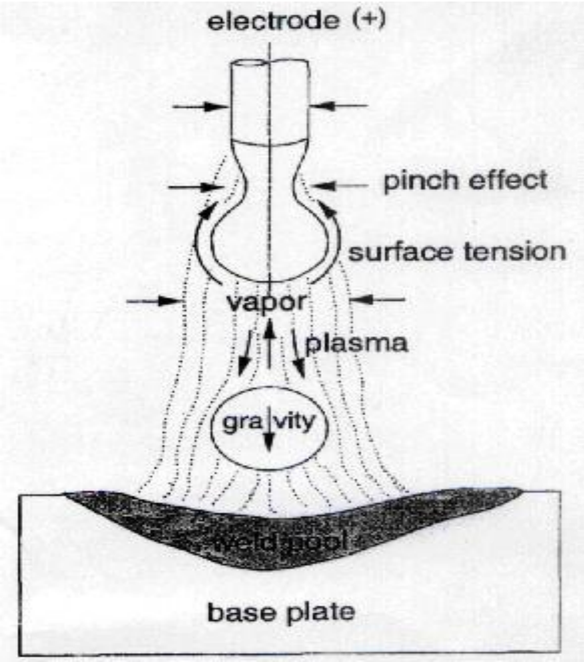


Figure 2: Forces acting on the drop [3]

The **gravitational force** is a detaching force when the electrode is pointed downwards as in down-hand welding and a retaining force when it is pointed upward as in overhead welding. Numerically, it is equal to the weight of the detaching molten droplet [4].

The **surface tension force** acts on the surface of the molten droplet and compresses the drop. It always tends to retain the molten metal drop regardless of the welding position. It, thus, naturally resists detachment [1].

Electromagnetic force creates a pinch effect, which helps transfer across the arc. When current flows through the electrode, a magnetic field builds up and surrounds it. The force acts on liquid metal drop when it is about to detach from the electrode. As the metal melts, cross sectional area of the electrode changes at the molten trip. When the molten drop diameter is larger than the electrode, the magnetic force tends to detach the drop. When there is a constriction, or necking down, which occurs when the molten drop is about to detach, the magnetic force acts away from the point of constriction in both directions. The drop, which has started to separate, is given a push which increases the rate of separation. This is known as pinch force (Fig. 3). The magnetic force also sets up a pressure within the molten metal drop. The maximum pressure is radial to the axis of the electrode, and at high currents causes the drop to become elongated. It gives stiffness to the drop and causes it to propel in line with the electrode, regardless of whichever direction the electrode is pointing, upward or downward [5]. Thus, it has two components: a **radial, pinching force** that squeezes the droplet (magnetic pressure), and an **axial force**. The direction of the axial force depends on the current distribution inside the droplet. It attaches the droplet with converging current, and detaches it with diverging current lines [6].

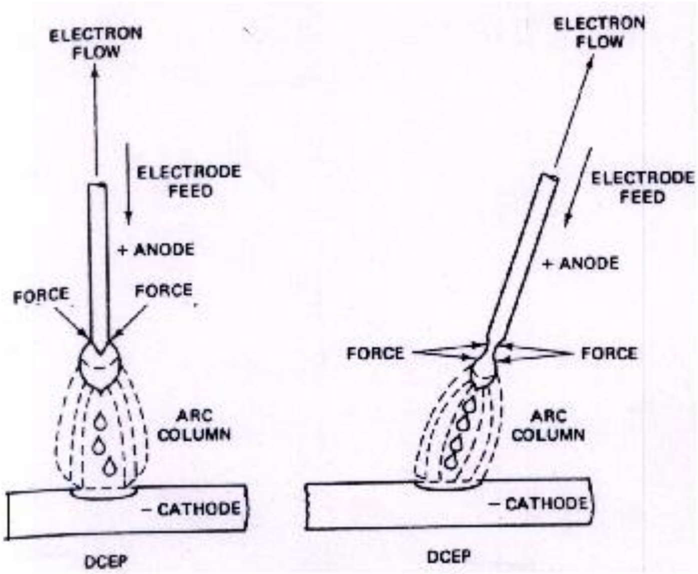


Figure 3. Electromagnetic forces on the drop [5]

The plasma drag force due to the flow of gas around the drop helps in detaching the droplet from electrode tip. The magnitude of this force may be affected by the amount of gas flow in GMAW [4, 5].

The mode of metal transfer is dependent upon the cumulative effect of these different forces acting on the molten droplet growing at the tip of the electrode. There are basically two independent theories of metal droplet detachment, and both predict the critical condition for droplet detachment.

1. **Static force balance theory (SFBT):** The theory was first proposed by *Greene* and further developed by *Amson, Waszink et al.* [7]. It claims that the droplet detaches from the electrode tip when the detaching forces on the drop exceed the retention forces. Detaching forces include gravitational, electromagnetic and plasma drag forces, while surface tension and vaporization forces are retention forces.
2. **Pinch instability theory (PIT):** The theory explains decrease of the droplet size with increase in the current intensity and the conditions for

instability of the molten metal column [8]. It is based on the consideration of the stability of the long, current-carrying liquid cylinder. It is known that even in the absence of any current, the disturbance that squeezes the liquid cylinder in some places and expands it in others can grow exponentially in time, if the wavelength of the disturbance is long enough (**Rayleigh instability**). This instability breaks the fluid cylinder into droplets. The size of the droplets is related to the wavelength of the fastest growing disturbance. When an electrical current is flowing along the liquid cylinder, the pinch effect further enhances the Rayleigh instability because magnetic pressure is higher in squeezed parts of the cylinder and lower in the expanded ones. As a result, the disturbances with shorter wavelengths become unstable in the presence of electrical current. This is the way PIT explains the decrease in droplet size with the increase in current [6].

Both SFBT and PIT fail to describe metal transfer properly. SFBT can predict the droplet size in globular transfer range (valid for low current) but it deviates significantly in the spray transfer range. The cause of deviation is geometry change of electrode due to a taper formation at the electrode tip. The PIT fails to explain the effect of the electrode extension or of changes in shielding gas on the metal transfer mode and is unable to predict the transition from globular transfer mode to spray transfer mode successfully. Other models have also been proposed to predict metal transfer more accurately [9].

In 1994, *Nemchinsky* [9] developed a steady state model to describe metal transfer by calculating the equilibrium shape of a pendant droplet. An equation to describe the droplet shape is proposed and solved. It calculates the maximum volume of droplet that can still be attached to the electrode, and then computes the radius of the detached droplet. This is the first model to include effects coming from the coupling between surface tension, electromagnetic force, and the droplet shape. It allows calculation of the detaching droplet size more accurately over a wider current range compared to the SFBT and PIT models.

All the models discussed so far are basically static approaches. They are still unable to predict the dynamic behavior of the droplet growth and detachment during metal transfer. The calculations tend to diverge as soon as the instability occurs.

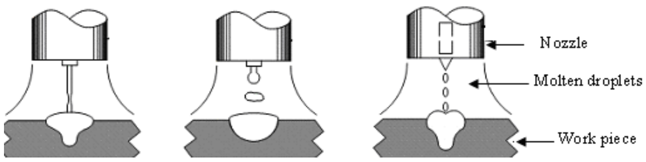
Simpson and Zhu [10] developed a one dimensional model considering the forces acting on the droplet. The model made the first predictions of droplet shape as a function of time. It is, however, not suitable for making adequate predictions of the transition current between globular and spray transfer modes, nor does it describe the details of the metal transfer process.

Haidar. [11] have developed a time dependent, two dimensional model for prediction of droplet formation that includes the arc, and predicts the transition from globular to the spray transfer mode. Surface tension, gravity, and magnetic pinch forces are considered. However, the model does not consider the arc drag force, droplet detachment, and the impingement of the droplets on the molten pool.

III. Modes of Metal Transfer

Mode of metal transfer refers to the manner or process by which the wire electrode is melted and deposited into the weld puddle. It determines the operating features of the process. The most common way to classify metal transfer is according to the size, frequency, and characteristics of the metal drops being transferred; other factors are current, wire diameter, arc length or voltage, power supply characteristics, shielding gas.

There are three traditional modes of transfer – short circuiting, globular and axial spray (Fig. 4). With more recent developments in power source technology, two higher level transfer modes – pulsed spray and surface tension transfer have been developed [12].



Short circuiting Globular
Axial spray

Figure 4: Modes of metal transfer [13]

3.1 Short Circuit Metal Transfer

American Welding Society defines short circuit gas metal arc welding (GMAW-S) as “a gas metal arc welding process variation in which the consumable electrode is deposited during repeated short circuits." Short circuiting arc transfer is also known as **short arc welding**, **short arc micro-wire welding**, **fine wire welding**, and **dip transfer**. Central to the successful operation of short circuiting transfer is the diameter of electrode, shielding gas type and welding procedure employed [12, 14].

Short circuit transfer gets its name from the welding wire actually "short circuiting" (touching) the base metal many times per second [13]. Metal transfer occurs when the electrode is electrically shorted (in physical contact) with the base material or molten puddle [12]. Molten droplets form at the tip of the electrode, but, instead of dropping, they bridge the gap between the electrode and the weld pool.

When the electrode touches the molten weld pool, the arc is no longer present; the current then begins to rise and heats the wire. The surface tension of the pool pulls in the molten metal from the end of the electrode. The rise in current accompanies an increase in the magnetic force applied to the end of the electrode. The electromagnetic field, which surrounds the electrode, provides the force that squeezes (more commonly known as pinch) the molten droplet from the end of the electrode (Fig. 2). The combined effect of surface tension and pinch force separates the molten metal and the electrode. The arc then reestablishes itself. The continuously fed electrode again touches the molten pool and the process repeats. The droplet transfer or short circuiting process repeats itself about 20-200 times per second [7, 12]. The sequence of events in the transfer of metal and the corresponding current and voltage are shown in Fig. 5.

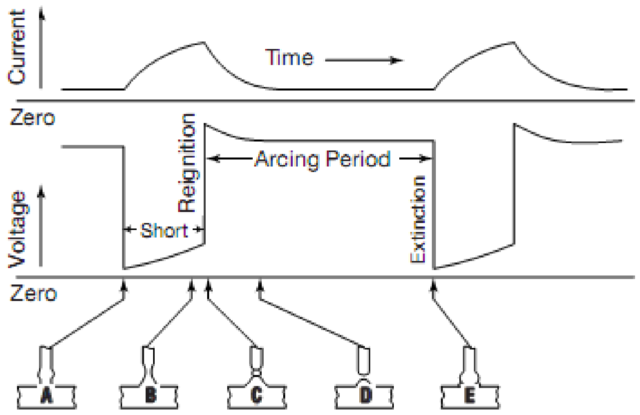


Figure 5: Oscillogram of short circuiting transfer [12]

A – Electrode makes physical contact with base metal. There is no arc, and current flows through electrode wire and base metal. Arc voltage approaches zero, and current level increases.

B – Heat of the current flow causes magnetic field to envelope the electrode wire. Resistance in the electrode wire increases causing it to heat, melt, and "neck down". Voltage slowly begins to climb through the period before detachment, and current continues to climb to a peak value.

C – This is the point where molten droplet is forced from the electrode tip. Current reaches its maximum value. Jet forces are applied to molten puddle, preventing it from rebounding and reattaching itself to the electrode.

D – This is the tail-out region of the short circuit waveform, and it is during this downward excursion toward the background current when the molten droplet reforms.

E – The electrode at this point, once again, makes contact with the molten puddle, preparing for the transfer of another droplet [12].

The frequency of the pinch force and the formation of droplets are controlled by the inductance of the power source. The relationship between the electrode melt rate and its feed rate into the weld zone determines the intermittent establishment of an arc and the short circuiting of the electrode to the workpiece. The electrode is fed at a constant speed at a rate that exceeds the melt rate [7, 14].

Since there is no arc established during the short circuit, the overall heat input is low, and the depth of fusion is relatively shallow. The weld pool freezes quickly, allowing for effective out-of-position welding. It generally operates at low voltages, with small diameter electrodes. The low heat input attribute makes it ideal for sheet metal thickness materials. The usable base material thickness range for short circuiting transfer is typically considered to be 0.024-0.20" (0.6-5.0 mm). However, the process lends itself to root pass applications on heavier plate open groove and pipe welds. This type of metal transfer provides better weld quality and fewer spatters than the globular variation [12].

Even though metal transfer occurs only during short circuiting, shielding gas composition has a dramatic effect on the molten metal surface tension. Changes in shielding gas composition may affect the droplet size and the duration of the short circuit. In addition, it influences the operating characteristics of the arc and base metal penetration. Carbon dioxide generally produces high spatter levels compared to inert gases, but it also promotes deeper penetration. To achieve a good compromise between spatter and penetration, mixtures of carbon dioxide and argon are often used when welding carbon and low alloy steels [15]. This mode of metal transfer typically supports the use of 0.025-0.045" (0.6-1.1 mm) diameter electrodes shielded with carbon dioxide either wholly or mixed with 75-80 % argon [12]. Stainless steel usually requires a mixture of helium, argon, and carbon dioxide [7].

Electrical stick-out must be closely controlled as it has a great impact on current levels. At the low end condition of 40-50 amps and 14-15 volts with a 0.023 " electrode, stick-out should be about $^1/_4$ ". With a 0.035" electrode at 80-90 amps and 15-16 volts, it should be about $^3/_8$". At the high end of short arc transfer with a 0.045" electrode, current should be at 225-235 amps and 20-22 volts [16].

Advantages of Short Circuit Metal Transfer

1. Because of its low heat input characteristics, the process produces small, fast-freezing weld puddles, which makes it suitable for welding in all positions, especially vertical and overhead, where puddle control is more difficult.
2. Short circuiting transfer is also adaptable to welding sheet metal with minimum distortion and for filling gapped or poorly fitted parts with fewer tendencies for burn-through of the parts; it is also capable of root pass work on pipe applications.
3. This type of metal transfer provides better weld quality than globular variation.
4. Higher electrode efficiencies, 93 % or more.

Limitations of Short Circuit Metal Transfer

1. The short circuiting transfer produces some spatter.
2. Lack of fusion and insufficient penetration when welding thicker materials due to lower arc energy. Cold lap and cold shut are additional terms that serve to describe incomplete fusion defects.
3. Restricted to sheet metal thickness range and open roots of groove joints on heavier sections of base material.

3.2 Globular Metal Transfer

Globular metal transfer occurs when the current and arc voltage are between those of short circuiting and spray transfer modes. Metal transfer in it occurs across the arc as large, irregularly shaped drops, at low current levels where the molten metal forms a large droplet on the end of the wire (Fig. 4) [7]. The droplet continues to grow until the downward gravitational forces acting on it become greater than the surface tension force when it detaches itself from the end of the wire. The diameter of the droplet is bigger (usually 1.3-2 times) than the diameter of the electrode wire. When the current is slightly increased, this large droplet may be repelled due to the electromagnetic forces [17].

When the drop finally detaches under gravitational force, it falls to the workpiece, leaving an uneven surface and often causing spattering. As a result of the large molten droplet, the process is generally limited to flat and horizontal welding positions. In vertical position, large molten droplet is deflected by gravity. The most widely used shielding gas for globular transfer is carbon dioxide since it is low in cost and allows globular transfer to take place at all usable welding currents [13]. Globular transfer uses higher voltages (25-35 volts) and high amperages (50-170 amps) depending on electrode size. One popular use of globular transfer is a mild steel electrode wire and carbon dioxide shielding gas. Some welders may refer to welding wholly with carbon dioxide or mixed with 75 % argon as being spray transfer, but technically at about 22 volts and higher, it is always a globular transfer. Also, production applications often find success using this mixture of shielding gases at amperages and voltages above short circuit transfer, but below spray arc transfer. An example is fillet welds on $^1/_4$ " mild steel, flat position using 0.035 " wire at 350 in/min welding speed and 25 volts. The arc sounds and looks like a short circuit, but is actually a modified spray or could also be called globular transfer [13].

The method was originally developed as a cost efficient way to weld steel using GMAW, because this variation uses carbon dioxide, a less expensive shielding gas than argon. Adding to its economic advantage was its high deposition rate, allowing welding speeds of up to 110 mm/s (250 in/min) [5].

Globular transfer is unstable, with a less smooth weld bead appearance. It can also cause cold lapping or incomplete fusion due to large metal droplets splashing metal out of the puddle. Depending on the current range, shielding gas and power supply settings, globular transfer can waste 10-15 % of the weld metal as spatter. GMAW with globular metal transfer is often considered the most undesirable of the four major GMAW variations [16].

One way to minimize spatter is using carbon dioxide, to increase current slightly and by adjusting voltage so that the tip of the electrode is below the surface of the molten weld pool. The arc is within a cavity generated by the force of the arc. This creates a deep weld pool that is below the metal surface, referred to as a **buried** or **submerged arc**. Using a buried arc, much of the spatter is contained within the deep weld pool, and a combination of globular and short circuiting transfer occurs together with deeper penetration. This is useful when making arc spot welds in heavy steel sections [5, 7].

Advantages of Globular Transfer

1. It is capable of making welds at very high travel speeds.
2. Uses inexpensive carbon dioxide shielding gas, frequently combined with argon.
3. It is a deep penetrating process. Because of its high voltage, amperage and wire feed speeds, it is a high deposition process mode.

Limitations of Globular Transfer

1. The presence of spatter.
2. A less desirable weld appearance than spray or pulsed spray transfer.
3. Welding limited to flat position and horizontal fillet welds only.
4. Welding limited to metal $^{1}/_{8}$" (3 mm) or thicker.
5. Prone to cold lap or cold shut and incomplete fusion defects which results in costly repairs.
6. High spatter level reduces electrode efficiency to a range of 87-93 % [12, 13].

3.3 Spray Metal Transfer

Spray transfer was the first metal transfer method used in GMAW. A spray transfer "sprays" a stream of tiny molten droplets across the arc, from the electrode wire to the base metal at a high frequency, as a result of high average current. These molten droplets are usually smaller than the diameter of the electrode wire [13].

The spray arc transfer uses, compared to short circuit transfer, relatively high values of amperage, voltage (≥ 24 volts) and wire feed speed, depending upon the type of shielding gas. As the current and voltage increase beyond the range of short circuit transfer, globular transfer takes place. When current reaches a critical level, the tip of electrode becomes pointed and a large number of very small drops are formed and detached at the rate of hundreds per second. This mode of transfer is called spray transfer. The critical value of current at which this transition from globular to spray transfer occurs is referred to as the **critical transition current** (Fig. 6). Sometimes spray transfer is called **axial spray transfer** where droplets are directed axially in a straight line from the electrode to the weld puddle [14].

The transition current zone between the globular and spray mode has great importance in the GMAW process, because it determines the working conditions of the process. Metal transfer mode affects the weld quality and welding productivity. The globular mode has limited applications, since it can cause lack of fusion, excessive reinforcement, and high amount of spatter in the weld bead. On the other hand, the spray mode generates excellent weld quality and high deposition rate at the weld bead, but it needs high welding energy (high current), and its application is indicated for thick plates. Another relevant factor in the knowledge of the transition current zone is its utilization in pulsed arc transfer, also known as controlled transfer [18]. The transition current varies with the electrode diameter, its composition, and the amount of electrode extension. A higher transition current is required for steel than aluminium. It increases with the electrode diameter and decreases as the electrode extends farther from the contact tube. For example, the transition current for 0.045" diameter steel filler metal is 220 amps [7].

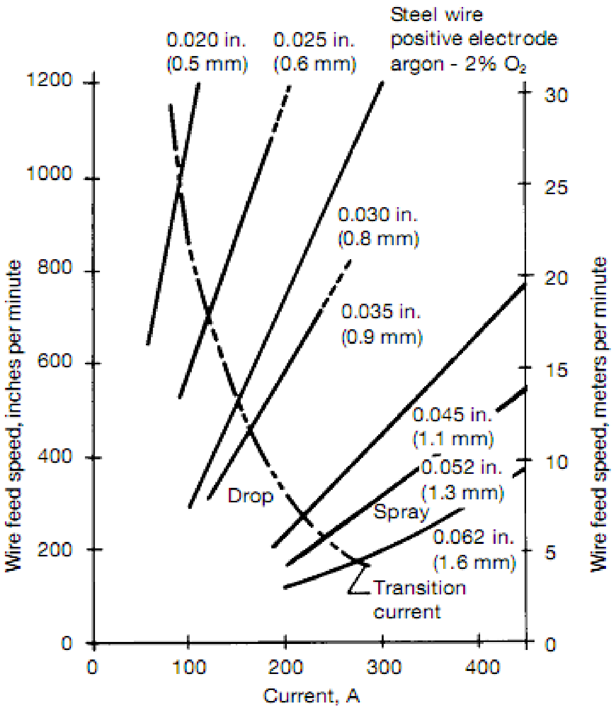


Figure 6: Burn-off curves of steel gas metal arc electrodes [19]

In spray arc transfer, the high density current leads to very high temperature of the molten droplet with consequential lowering of surface tension. As the current density increases, the droplet growth rate increases proportionately to the increase in temperature. Electromagnetic forces in the form of pinch effect become significant and outweigh surface tension. With high pinch force, the end of electrode is constricted at all the times, which physically limits the size of the molten metal droplets that form. Thus, only small droplets are formed, which transfer across the arc at relatively high frequency [20].

Depending upon the current density, spray mode has three different stages –projected, streaming and rotating transfers (Fig. 7). In globular range of metal transfer the current is too low to form necessary jet and pinch forces for detachment of the droplet. As current is increased the transition from globular to projected spray occurs. In **projected spray**, also referred to as **drop spray**, the droplets detach from the tip of electrode when they are much smaller than in globular transfer. Drop spray is found to give least spatter and smoke with higher deposition efficiency than other variants of spray mode. With the increase in current, the end of electrode gets tapered and fine spray of drops as a real shower streams off and the transfer becomes "**streaming**". This type of transfer is associated with well developed plasma jet as evidenced by the vapor stream. Finally, at very high values of the welding current, the molten metal is purely flowing, but the stream is **rotating**, due to the strong electromagnetic fields generated by the high values of the current [17, 4].

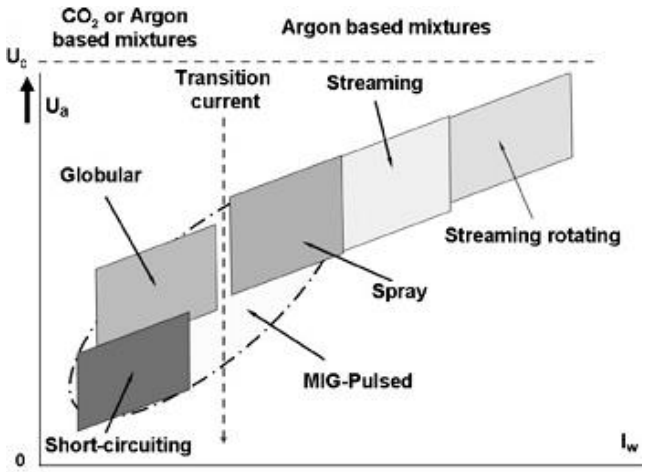


Figure 7: Arc voltage v/s welding current for various metal transfer modes [17]

Spray transfer occurs only when at least 90 % Ar is used as the shielding gas. Common shielding gas mixtures for carbon and low alloy steels are: 98 % Ar + 2 % O_2, 95 % Ar + 5 % O_2, 95 % Ar + 5 % CO_2, and 90% Ar + 10 % CO_2 [7].

Spray transfer GMAW produces good weld appearance and the least spatter of any mode of metal transfer. High heat input results in good penetration and deposition rate, but its application is limited to mostly flat and horizontal (lap and T-fillet) welding. It is generally used on workpieces of thicknesses above 6.4 mm (0.25"); the high heat input could cause excessive melt-through on thinner metals. The maximum deposition rate is relatively high, about 60 mm/s (150 in/min). For most applications in the 175-400 amp range, 0.035" to $^{1}/_{16}$" wires work well. When the welding equipment is set up properly, there is almost no spatter and 97-98 % of the filler metal is deposited in the weld puddle (deposition efficiency) [16].

Axial spray transfer may be used with all common alloys including aluminium, magnesium, carbon steel, stainless steel, nickel and copper alloys [12].

Advantages of Spray Transfer

1. High deposition rates.
2. High electrode efficiency of 98 % or more.
3. Employs a wide range of filler metal types in an equally wide range of electrode diameters.

4. Excellent weld bead appearance.
5. Presence of very little, if any, spatter.

Limitations of Spray Transfer

1. Restricted to flat and horizontal welding positions.
2. Welding fume generation is higher.
3. The higher radiated heat and the generation of a very bright arc require extra welder and bystander protection.
4. The use of axial spray transfer at outdoors requires the use of a windscreen.
5. The shielding used to support axial spray transfer costs more than 100 % CO_2.
6. It is generally not practical for root pass welds.

3.3.4 Pulsed Spray Metal Transfer

Pulsed spray metal transfer mode, a more recently developed method, is a controlled method of spray transfer, in which the arc current is maintained at a value high enough to permit spray transfer and for long enough to initiate detachment of a molten droplet. Once the droplet is transferred, the current is reduced to a relatively low value to maintain the arc. The period of low current allows the average arc current to be reduced into a range suitable for positional welding, while periodic injection of high current pulse allows metal to be transferred in the spray mode. It uses a pulsing current to melt the filler wire and allow one small molten droplet to fall with each pulse [20].

Globular and short circuiting metal transfers typically cause significant spatters and poor weld quality. Their application in production is limited. The spray transfer mode has advantages over the other modes with its regular detachment accompanied by uniform droplet size, directional droplet transfer and low spatters. However, it is only 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. Hence, its application is restricted [14]. During the mid 1960s, an alternative transfer technique of pulsed gas metal arc welding (GMAW-P) was invented. This mode of metal transfer overcomes the drawbacks of globular mode while achieving the benefits of spray transfer. It is characterized by pulsing of current between low level **background current** and high level **peak current** in such a way that mean current is always below the threshold level of spray transfer (Fig. 8) [21].

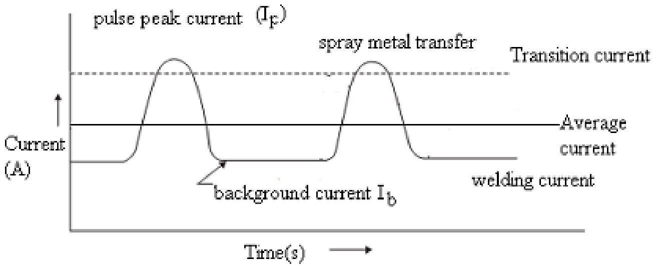


Figure 8: Pulsed Spray GMAW [18]

A low level current, called the background current, in the globular transfer range, is used to maintain the arc. It is increased at a regular frequency to a peak value above the **transition current** level. Since the background current is on for only a short time, no globular transfer actually occurs. During the peak current time period, spray transfer occurs [7].

When the current increases form background current (typically 20-40 amps) to the peak value, the wire is melted into a singular droplet and is transferred across the arc in pulsed spray transfer (Fig. 9). Ideally, one droplet is transferred during each pulse. The pulsing rate can be varied depending on the base material, thickness, and weld position. The period of background current maintains the arc and heat input [14, 16].

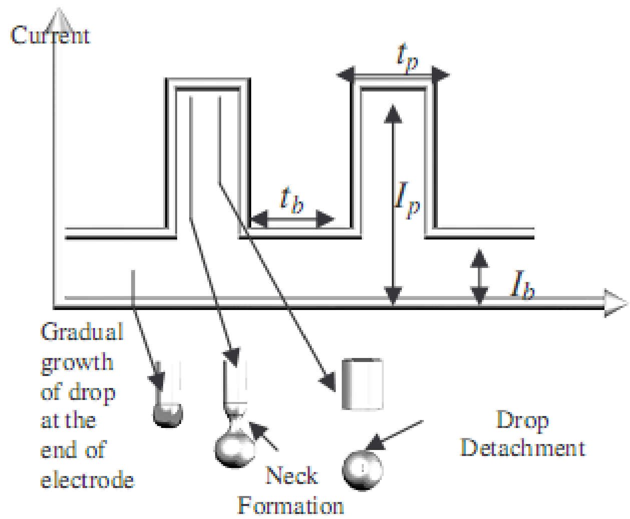


Figure 9: Pulsed current waveform [22]

Because there is no metal transfer during the background portion of the cycle, the weld puddle gets a chance to freeze slightly. This faster freezing weld puddle is what allows the pulsed spray transfer to be used for thinner metals, and for better control on out-of-position work. GMAW-P often allows for larger wire sizes to be used on varied metal thicknesses. Because of the small size of the droplet, spatter is minimized and penetration is easily controlled due to the lower average currents when compared to spray transfer. Power source is capable of providing current pulses with a frequency of 30-400 pulses per second [14]. The process is widely used for thin sheet metal joining especially with aluminium [22].

The mode employs electrode diameters from 0.030-0.0625" (0.8-1.6 mm). It is used for welding a wide range of material types. Argon based shielding gas selection with a maximum of 18 % carbon dioxide supports the use of pulsed spray metal transfer with carbon steels.

Pulsed spray transfer process uses a special power supply that switches the welding current between a peak current and a low background current level for a fixed period of time. In doing so, there is a greater control of the metal transfer [12].

The main setting parameters which influence weld quality or wire melting are background current I_b, peak current Ip, background time t_b, and peak time tp. Two additional parameters, namely frequency $f = 1 / (tp + t_b)$ and duty cycle $D = t_p / (t_p + t_b)$ are introduced to simplify parameter setting [22].

For achieving controlled transfer during pulse welding, it is essential that wire feed rate is balanced by burn-rate. This means achieving one drop per pulse condition all the time, which involves constant control of all the pulse parameters [23]. The welding parameters are more numerous than in conventional GMAW, and the process is typically more sensitive to parameter changes. As a result, careful parameter selection is important. To address this, the advanced "synergic" pulsed GMAW power supplies are commonly used in industry. In these systems, the relationship between a digitally controlled wire feed rate and the pulsing parameters is managed by microprocessor with appropriate software [24].

Advantages of Pulsed Spray Transfer

1. Absence or very low levels of spatter.
2. Excellent weld bead appearance.
3. Reduced levels of heat induced distortion.
4. Ability to weld out-of-position welding on both light (< ⅛ " thick) and heavy gauge metal thicknesses.
5. Reduces the tendency for arc blow.
6. When compared to flux-cored arc welding (FCAW), SMAW, and GMAW-S, pulsed spray transfer provides a low cost, high electrode efficiency of 98 %.
7. Lends itself to robotic and hard automation applications.
8. Capable of arc travel speeds greater than 50 in/min (1.2 m/min).

Limitations of Pulsed Spray Transfer

1. Equipment to support the process is more expensive than traditional systems.
2. Blends of argon based shielding gas are more expensive than carbon dioxide.
3. Higher arc energy requires the use of additional safety protection for welders and bystanders.
4. Adds complexity to welding.

3.5 Modified Short Circuiting Transfer

There are proprietary derivatives of the short circuiting transfer mode which use a modified waveform to reduce some of the problems found with short circuiting, mainly spatter and a turbulent weld pool. Typically these systems sense the progression of the short circuit as it happens and modulate the current to limit the amount of force behind spatter and turbulence producing events. Several manufacturers now sell welding power supplies which employ technology to this end. *Miller Electric* has a process called RMD (Regulated Metal Deposition). *Lincoln Electric* sells their process called STT (Surface Tension Transfer). *Fronius* has a technique called CMT (Cold Metal Transfer) which physically withdraws the electrode from the welding puddle at a certain rate and pattern.

IV. Parameters Affecting Metal Transfer Mode

The operational variables affecting the mode of metal transfer are welding current, electrode polarity, shielding gas composition, electrode extension and welding material.

4.1 Welding Current

Among all the variables, welding current is the most common that operator adjusts to obtain the desired metal transfer mode. As the current increases, the metal transfer mode changes. At low welding currents globular transfer occurs, while spray transfer occurs at higher welding currents [7].

The current at which transition from globular to spray transfer begins (the transition current) depends on a number of factors including the composition of the consumable electrode, electrode diameter, electrode extension, and composition of shielding gas. A great difference in the transition current is found with different metal systems comprising the consumable electrode. Since they are the most widely used consumable electrode compositions, it is particularly interesting that there are great differences between steel and aluminium. Transition currents for various sizes of steel and aluminium electrodes are shown in Table 1.

Table 1: Arc currents for transition from globular to spray metal transfer [1]

Electrode diameter		**Transition current, amp**	
mm	inch	Steel (Ar + 2 % O_2)	Aluminum (Ar)
0.75	0.030	155	090
0.90	0.035	170	095
1.15	0.045	220	120
1.60	0.062	275	170

The amount by which a consumable electrode extends past the contact tube in a GMAW torch affects transition current (Fig. 10). An increase in electrode extension or “stick-out” allows a slight decrease in the current at which spray transfer develops [3].

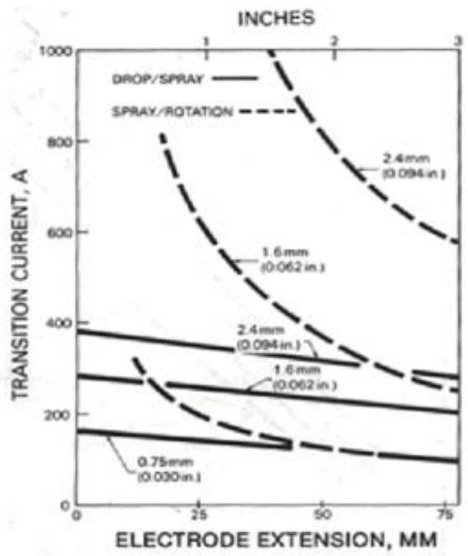


Figure 10: Effect of electrode extension and diameter on transition current [3]

4.2 Shielding Gas

Different shielding gases can have quite different effects on the mode of molten metal transfer. For example, helium does not usually produce an axial spray; regardless of current level or polarity, transfer remains globular. Pure helium remains attractive, however, because helium shielded arcs provide deeper penetration as a result of higher work function of this gas. Spray transfer can be obtained by mixing it with relatively small quantities (20-25 %) of argon without adversely affecting penetration.

Spray transfer is also difficult to achieve with active gases such as nitrogen or carbon dioxide. Treatment of the wire electrode’s surface with alkali metal compounds is necessary, but often not practical. Other problems arise with active gases, however, such as greater arc instabilities and chemical reactions between the gas and the superheated molten metal drops that cause considerable spatter. This difficulty can be overcome, at least to some degree, by employing the short circuiting technique and burying the arc below the plate surface to trap the spatter in the deep arc crater. Similar treatment is required for welding copper with nitrogen shielding and argon-nitrogen mixture for aluminium alloys [25].

Short circuiting transfer is optimized using mixtures of 20-25 % carbon dioxide in argon, although higher percentages are typically used for welding thick steel plate. Finally, small quantities of oxygen (2-5 %) or carbon dioxide (5-10 %) are commonly added to argon to stabilize the arc, lower or raise the globular to spray transition current, respectively, and improve wetting and bead shape, especially for welding steel [1].

The choice of shielding gas affects welding quality through its influence on metal transfer and also has a direct impact on welding costs. CO_2 is easily available and less expensive than Ar; however, weld bead quality and deposition rates often decrease with the increase of CO_2 in a binary Ar-CO_2 mixture. Currently, Ar costs 2-3 times as much as CO_2. If it were possible to create welds of the same quality and deposition rates using high Ar mixtures, with less expensive mixtures containing significant amounts of CO_2, the savings in the welding industry would be substantial [57].

Figure 11 schematically illustrates how different shielding gases lead to different types of molten metal transfer, weld bead contours, and weld penetration patterns.

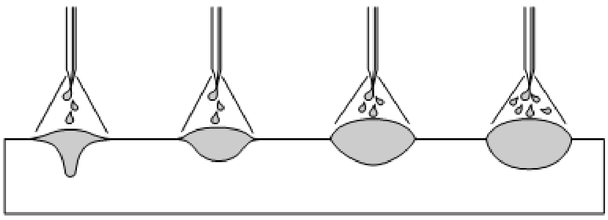


Figure 11: Bead contour and penetration patterns for various shielding gases [4]

4.3 Electrode Polarity

Since the GMAW process is almost always performed with electrode positive (DCEP) power, electrode negative (DCEN) operation is unlikely but possible. For DCEN, GMAW arcs tend to become unstable and spatter tends to be excessive. Furthermore, in this mode, droplet size is large and arc forces tend to propel drops away from the workpiece. Alkali metal compounds applied to the wire can help, but are generally of little practical consequence.

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