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REVIEW ARTICLE **Open Access**

Usability of arc types in industrial welding

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Abstract

Arc behaviour is a significant factor in all arc welding processes. Understanding of arc types and their inherent properties can help enhance weld prediction and weld quality and reduce welding cost and production cycle time. Advanced welding processes utilize real-time control and prediction, increasing the need for detailed knowledge of arc characteristics and arc applications. This paper analyses the types of welding arcs used in the welding industry, explains corresponding features and characteristics, provides guidance for suitable applications, and presents arc type comparisons, benefits, and weaknesses. The study is based on a review of the literature, and it provides a comprehensive overview of arc phenomena. The results of this work show that in many applications, greater benefit accrues from spray and pulsed arcs than short and globular arc modes. Controlled short arc, heavy deposition rate arc, and controlled spray arc are enhanced arc processes offering significant improvements in efficiency and usability. This review can assist companies in making appropriate choices of arc and welding process for different materials and applications. Furthermore, it can be utilized as a basis for further research.

Keywords: GMAW; Arc characteristics; Usability; Efficiency; Controlled arc

Review

Introduction

Arc welding is a key process in industrial manufacturing (Naidu et al. 2003), and gas metal arc welding (GMAW) is commonly used in many manufacturing process industries due to its fundamental advantages, such as adjustable penetration profiles, smooth bead, low spatter, and high welding speed (Kah et al. 2009). In the past two decades, GMAW has become the main technology in the robotic welding industry (Chen and Wu 2009). Arc type is an important factor in many applications; however, the arc phenomenon is not fully explained and exhibits unknown properties and behaviours.

Use of an appropriate arc type in welding of different materials with different thicknesses creates cost savings, reduces production times, and improves quality. The joining of thin materials and materials sensitive to heat has lately become an important issue. Improved understanding of arc phenomena can help develop and refine integrated design for industrial welding systems (Iordachescu and Quintino 2008). With an increasing variety of materials being joined and many different arc processes, the need to understand the different types of arc welding processes is more urgent than ever. Furthermore, when controlling and modifying the welding process, knowledge of the arc phenomenon will make it easier to produce improved weld quality and reliable joints (Eagar 1990a, b).

This study gives a brief introduction to arc characteristics, discusses classification of welding arcs, presents a comparison of arcs, and discusses the benefits and weaknesses of different arcs. Finally, types of welding arcs and their role in industrial applications are examined.

Arc characteristics

The welding arc can be seen as a conductor of gas that transforms electrical energy into heat energy (Naidu et al. 2003). In the study by Lancaster (1984), the welding arc is viewed as a cylinder-shaped body of gas that is confined by the temperature gradient. One problem commonly faced by the welding industry is poor stability of the arc. Arc stability and arc length influence the behaviour of metal transfer (Pal et al. 2010). With a stable arc, metal transfer is uniform and the amount of spatter is minimal (Hermans and Ouden 1999). In a stable arc situation, a relationship can be found between the voltage and current, shown in Figure 1 (Ibrahim Khan 2007). The graph shows that the arc does not follow Ohm's law. Furthermore, the decreasing part of the arc characteristic is Ayrton's part and is characterized by unstable arc, while the Ohm's part,

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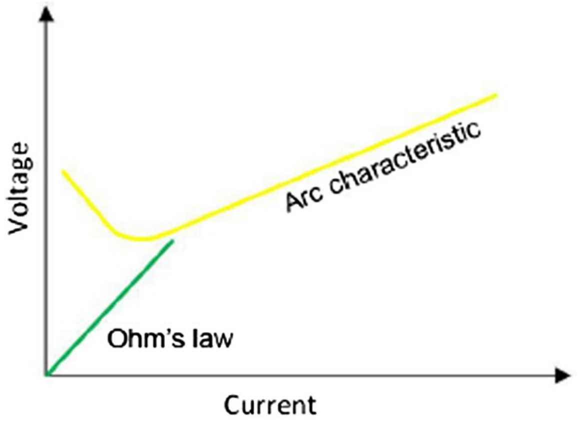

Figure 1 Typical arc characteristic compared with Ohm's law (Ibrahim Khan 2007).

increasing area is the one applied in welding. Other factors such as the arc atmosphere, arc length, and metals involved also have an influence on the slope of the curve.

Arc plasma

The arc plasma is the ionized state of the welding gas and is a mixture of almost equal amounts of electrons and ions. The plasma carries the arc current. Most of the current conduction is carried by the electrons. In the case of arc welding, the electrode is generally assumed to be the cathode and the workpiece is the anode. The electrons flow out from the electrode (i.e. the negative terminal) and are forwarded into the workpiece (i.e. the positive terminal) (Naidu et al. 2003). To determine the effects of arc plasma on the weld pool, four factors should be considered (i) heat flux, (ii) current density, (iii) shear stress, and (iv) arc pressure.

There is a direct relation between increasing heat flux and current density and the depth of the weld pool. Increasing the shear stress at the molten pool promotes the outward flow at the top of the weld pool, and increasing the arc pressure can lead to a more concave surface of the weld pool (Murphy et al. 2009). However, arc pressure has no influence on the flatness of the weld pool surface when the current is less than 200 A (Lin and Eagar 1985; Wang and Tsai 2001).

Arc temperature

Initially, the temperature of the welding arc was considered to consist of the heat of the arc plasma but Cobine and Burger (1955) showed that most of the heat transferred to the workpiece from the electrode originates from the flow of the current into the metal. Later, this insight was extended by Quigley et al. (1973) who noted that only 20% of the heat is carried by conduction from hot gases and 80% remains in the electric current. Depending on the precise nature of the plasma and the amount of current flowing through it, the welding arc temperature varies from 5,000 to 30,000 K (Naidu et al. 2003; Robert and Messler 2004). In some cases, the power is extremely high and the temperature can rise up to 50,000 K (Naidu et al. 2003).

Two significant factors influence the plasma temperature: the particular plasma and its density (Robert and Messler 2004). In arc welding with a one-component gas, which is found in some welding processes, the temperature is lower in GMAW because the molten droplet, vapour, and metal ions are more concentrated. Figure 2 shows an arc temperature distribution in GMA welding of aluminium at 250 A. As can be observed, the central core of the arc has the highest temperature, which changes depending on the shielding gas used (Robert and Messler 2004).

Arc current

The welding process is affected by several factors, such as arc current, arc voltage, travel speed of the torch, filler wire, and spin frequency (Lu et al. 2009; Moon et al. 2006). When selecting these parameters, the amount of heat input and the desired fusion should be considered (Min et al. 2011). The mode of the arc, and therefore the weld quality, is greatly influenced by the current (Hu and Tsai 2006). The penetration depth is also significantly affected by the arc current. In gas metal arc welding, increase in the arc current increases joint penetration. However, increased joint penetration also increases the possibility of burn-through and solidification cracking. Experiments done by Hu and Tsai (2006) showed that a higher current leads to a higher electromagnetic force, which causes the droplet to detach from electrode to the weld pool. Furthermore, with a higher current, the size of the molten droplet is smaller and there is a higher droplet frequency.

Arc voltage

The arc voltage is proportional to the arc length. Therefore, the arc voltage can be controlled by changing the arc length (Naidu et al. 2003). Figure 3 shows the arc voltage curves of a typical power source within a welding current and voltage diagram. It can be seen that a small change in

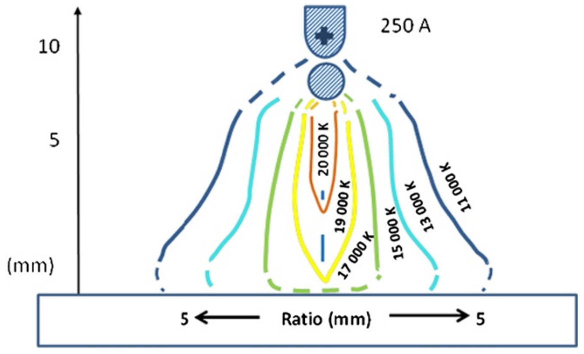

Figure 2 Arc temperature distribution in GMA welding of aluminium at 250 A (Smårs and Acinger 1968).

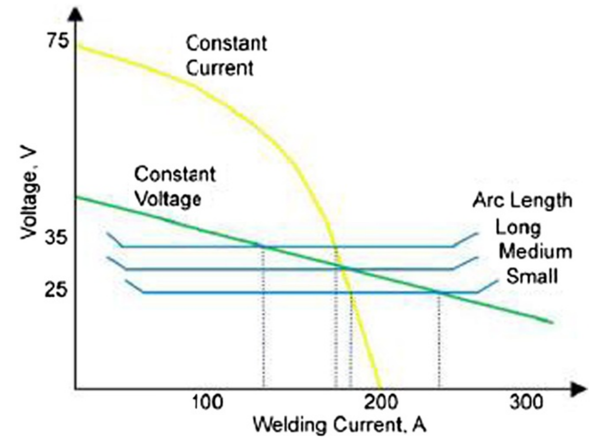

Figure 3 Self-regulation of arc voltage (Naidu et al. 2003).

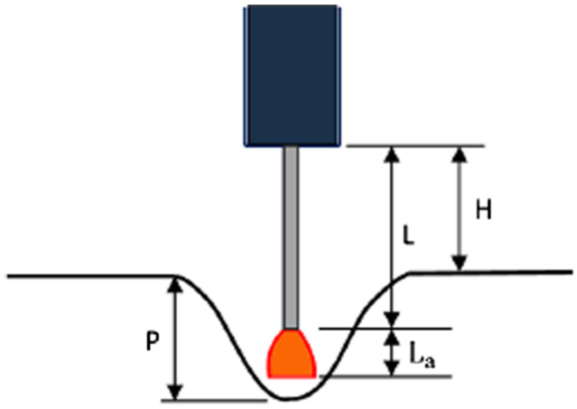

Figure 4 Parameters to predict the arc position (Iwata et al. 2009a, b).

voltage results in a very large change in the welding current. As a consequence of the relationship between welding current and arc voltage, weld properties and geometry can be predicted (Shoeb et al. 2013): welding with a high voltage produces a very wide bead with possible undercuts and a concave shape, and welding with too low a voltage produces a low-quality weld bead.

As can be seen from Figure 3, the voltage changes significantly with small change in arc length while low variation occurs for the current. Consequently, the arc length has more effect on the voltage than on the welding current. The arc length in this diagram is divided into three parts: long, medium, and small, which are so-called voltage source curves. The junction of the CC and CV curves with the voltage source curve is called the operating point of power supply and can be changed during the welding process (Naidu et al. 2003).

Arc penetration

To determine arc penetration, it is necessary to know the arc position, which is computed from parameters such as the welding voltage, welding current, and wire feed speed. The arc position is defined as the sum of the wire extension and the arc length. In Figure 4, these parameters are shown for GMAW by L and L_a, respectively. The distance between the welding torch and workpiece is H, and the parameter P depicts the depth of penetration (Iwata et al. 2009a, b).

Figure 5 illustrates the correlation between the arc position and penetration during the welding of flat plates by SAW. The fitting line on the graph shows that the values of arc penetration and arc position are very close. The relationship is therefore as anticipated (Iwata et al. 2009a, b).

Arc efficiency

Arc efficiency is an important factor in arc welding processes and is generally explained as the heat input into the metal divided by the total heat energy of the arc (Eagar 1990a). In other words, arc efficiency is measured as the amount of arc energy delivered to the substrate (Dupont and Marder 1995). Arc efficiency has an effect on the welding rate and can vary from 60% to 99% for different welding processes (Eagar 1990b). It is essential to know arc efficiency in order to measure the melting efficiency, both by experiment and by utilizing heat-flow models (Dupont and Marder 1995). Welding parameters (e.g. current and voltage) have few effects on arc efficiency for a given process, and the arc efficiency of non-consumable electrode processes is considered to be a bit lower than that of consumable processes (Kou 1987; Lancaster 1984). Heat input can be calculated using arc efficiency by the formula shown in Equation 1 (Gunaraj and Murugan 2002):

$$\text{Heat input}\left(\frac{\text{kJ}}{\text{cm}}\right) = \frac{\text{Arc voltage} \times \text{Arc current}}{\text{Welding speed} \times 1,000} \times \text{Arc efficiency} \tag{1}$$

Arc stability

Arc stability is another important characteristic of arc welding. Arc stability is influenced by parameters such as

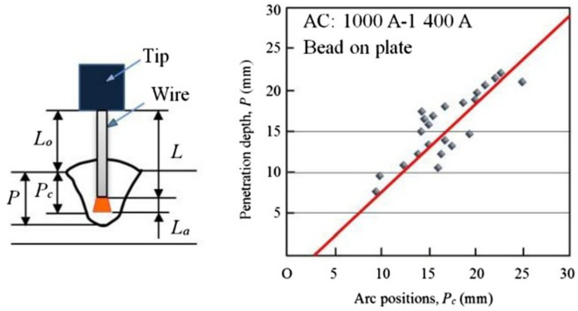

Figure 5 Comparison between predicted and actual penetration depth for SAW (Iwata et al. 2009a, b).

arc power, metal transfer mode, and the regularity of the metal transfer mode (Ghosh et al. 2006). The emission of spatter during welding is the main negative result of poor arc stability; spatter creates material losses, extends cleaning time, and decreases weld bead quality (Suban and Tusek 2003).

The properties of an ideal and stable welding arc are as follows (Suban and Tusek 2003): (i) the shape of all transferred material is constant, (ii) the length of the arc is constant, and (iii) there is a low level of spatter or no spatter at all.

During welding with a consumable electrode, e.g. GMAW, arc stability is affected by the behaviour of the arc root (Costa et al. 2010). Another factor in arc stability is the shielding gas mixture. The stability of the arc is lower in a gas mixture with higher carbon dioxide (CO_2) content. Figure 6 shows that longer arc length and thinner isothermal distribution are two characteristics of a mixture with a low carbon dioxide content (Pires et al. 2007).

Arc blow

Arc blow is a phenomenon in which the arc tends to become separated from the point of welding, as though a strong wind were blowing (Naidu et al. 2003). The reason for the occurrence of arc blow is imbalance in the magnetic field surrounding the workpiece (Gerbec 2009). Generally, this phenomenon occurs in three situations: (i) the direction of the current changes, (ii) there are magnetic materials around the welding arc, and (iii) there are magnetic materials near the edge of the plate (Naidu et al. 2003). Arc blow is generally found only with high DC welding currents. It can be prevented by reducing the current level, by using an AC welding current, and by demagnetizing the fixture (Gerbec 2009). Arc voltage affects arc deflection such that an arc with a lower voltage is shorter and stiffer and has better resistance to deflection than an arc with a higher arc voltage.

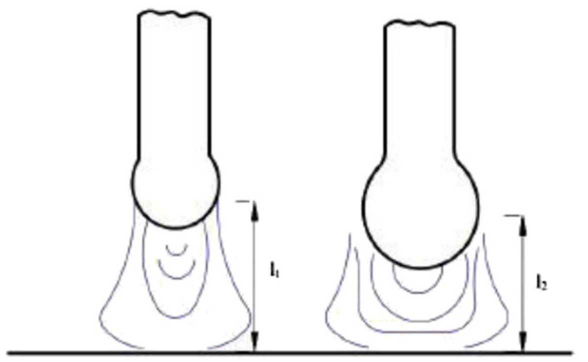

Figure 6 Temperature distribution for mixtures: high (left) and low (right) content of carbon dioxide. For the same current and voltage, l_1 is higher than l_2 (Pires et al. 2007)

As mentioned earlier, the arc's heat energy is created by electrical reactions between the anode and cathode area inside the plasma. Parts of the energy generated melt the electrode. The melting rate (MR) is influenced by the cathode heating (current) and can be calculated by the formula shown in Equation 2.

$$\mathrm{MR} = \alpha I + \frac{\beta}{\alpha_\omega} l_s I^2 \tag{2}$$

In the given formula, both α and β are constants, l_s is electrode resistivity, α_ω is the cross-sectional area of the wire, and I is the welding current (Naidu et al. 2003).

Pinch effect

The arc in all conductors carrying current is surrounded by a magnetic field (Luksa 2006). In arc welding, the cross-sectional area of the consumable electrode varies, and the direction of the electromagnetic force depends on the flow direction of the welding current. The magnetic field has a force that is directed to the center of the arc, the so-called Lorenz force. With increasing amperage, the amount of current and the arc radial constriction increase, due to the greater magnetic force. This process is called the pinch effect (Dzelnitzki 2000; Robert and Messler 2004). The amount of pinch force has a direct relation to the welding current and the diameter of the wire and has an influence on drop detachment to the weld join (Kasikci 2003). The pinch effect is shown in Figure 7 (Nadzam 2006).

When the cross-sectional area of the electrode increases, the Lorentz force is exerted in the same direction as the current flow. Decreasing the cross-sectional area of the electrode causes the Lorentz force to act in the reverse direction to the current flow. The Lorentz force can act in two ways to detach droplets from the electrode tip to the weld pool. First, if the electrode is positive and the size of the droplet is larger than the diameter of the wire electrode,

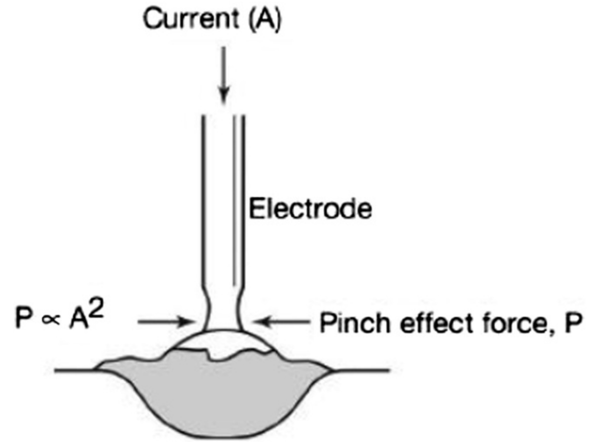

Figure 7 Pinch effect during short-circuiting transfer (Nadzam 2006).

the magnetic force separates the drop. Second, there is a constriction or necking down. In this case, the magnetic force acts in both directions away from the point of the constriction (Robert and Messler 2004).

Arc types

Following the first classification of arc types in 1976 (Lancaster 1984), several further classifications have been proposed. Short arc, globular arc, and spray arc are the three major classifications of arc types by the American Welding Society (AWS) (Iordachescu and Quintino 2008). The International Institute of Welding (IIW), in 1984, divided spray arc types into the three categories: (i) drop spray or projected spray, (ii) rotating spray, and (iii) streaming spray (Iordachescu and Quintino 2008; Lancaster 1986). Norrish (2003) and then Ponomarev et al. (2003) modified this categorization. Utilization of digital control of power sources has led to many improvements in arc control, especially in welding with short and pulsed arcs. Digital control increases the reaction speed of the power source inverter and the use of sophisticated software makes it possible to directly influence the arc (Weman 2003; Iordachescu and Quintino 2008).

Table 1 summarizes the attempt to classify metal transfer. Utilization of digital control of power sources has led to many improvements in arc control, especially in welding with short and pulsed arcs. Digital control increases the reaction speed of the power source inverter and the use of sophisticated software makes it possible to directly influence the arc (Weman 2003; Iordachescu and Quintino 2008). The current IIW arc classification is shown in Table 2. The table also includes an example welding process and the dominant force for each type of transfer mode (Iordachescu and Quintino 2008; Robert and Messler 2004).

Different factors have motivated efforts to classify arc and metal transfer, among them, a need for better understanding of the process to be able to examine and control it better. Better classification has allowed distinction of the arc based on droplet transfer. Thus, depending on the arc stability, desirable (e.g. bridging, spray) or undesirable (e.g. repelled, explosive) metal transfer can occur.

In bridging transfer, the molten metal grows until it touches the weld pool. A short circuit occurs and current rises; thus, the constriction and the breaking detach the droplet. In flight transfer, no contact exists between the electrode wire and the weld pool (Li and Zhang 2007). If the size of drops detached from the electrode to the molten weld pool is smaller than the diameter of the electrode wire, the arc mode is projected spray. If the molten metal from the electrode rotates, it is called rotating spray arc. Projected spray is mostly called spray arc to simplify the terminology (Robert and Messler 2004). Characteristics that are generally typical of a projected spray arc are steady detachment, low spatter, constant size of the droplet, and direct droplet transfer. Therefore, this mode of arc is preferred in conventional GMAW (Li and Zhang 2007).

Arc modes are related to arc voltage and the level of current. By changing these two parameters, the modes of the arc can be changed. With small current, the droplet does

Table 1 Summary of metal transfer mode evolution

Classification basis	Description	References
Droplet transfer	Free flight, short circuiting. A slag mode is defined for other arc welding (SAW)	IIW (1976), referred by Lancaster (1984) as Anon
Droplet transfer and droplet size	Categorization by level of current and drop size current: moderate current (globular), relatively high current (spray), high current (stream), very high current (rotating)	Lancaster (1984)
Associated transfer mechanism	Mechanisms: (1) natural metal transfer, (2) controlled transfer techniques, and (3) extended operating mode techniques	Norrish (2003)
Transfer mechanism and labelled with alphabet letters	Suggested confining the classification to natural and controlled transfer modes. In addition, these authors proposed an extra fixed alphabetic label for each 'fundamental' metal transfer mode (A, short-circuiting; B, globular; C, pulsed; D, spray; and E, rotating)	Lucas et al. (2005)
Current range, sketch illustration, and type of consumable electrode	Droplet transfer during GMA welding with solid wire and FCW has been observed in detail and the transfer The range of current is provided for each transfer mode	Izutani et al. (2006)
Sketch illustration of the mechanisms and an alphabetic associated with number classification	A, short-circuiting; B, globular; C, spray. Similar approach using alphanumeric labels (A, B1, B2, C1, C2, and C3). The controlled processes classification and defined two types of controlling processes, either simple controlled processes or real-time controlled processes.	Iordachescu and Quintino (2008)
Metal transfer-natural transfer, controlled transfer and mixed mode transfer, oriented to scientific personnel	Metal transfers are illustrated by a sequence of droplet transfer. Corresponding main forces governing the metal transfer are indicated for each case. Metal transfer modes are categorized in a flow chart: natural transfer, controlled, and interchangeable transfer.	Scotti et al. (2012)

Table 2 IIW classification of metal transfer mode and examples of welding processes[a]

Transfer type	Welding process (example)	Dominant force or mechanism
1. Free flight transfer		
1.1. Globular		
1.1.1. Drop	Low-current GMA	Gravity and electromagnetic pinch
1.1.2. Repelled	CO_2-shielded GMA	Chemical reaction generation vapour
1.2. Spray		
1.2.1. Projected	Intermediate-current GMA	Electromagnetic pinch instability
1.2.2. Streaming	Medium-current GMA	Electromagnetic
1.2.3. Rotating	High-current GMA	Electromagnetic kink instability
1.3. Explosive	SMA (coated electrode)	Chemical reaction to form a gas bubble
2. Bridging transfer		
2.1. Short circuiting	Short-arc GMA	Surface tension plus electromagnetic forces
2.2. Bridging without interruption	Welding with filler wire addition	Surface tension plus (hot wire) electromagnetic forces
3. Slag protected transfer		
3.1. Flux wall guided	SAW	Chemical and electromagnetic
3.2. Other modes	SAM, cored wire, electroslag	Chemical and electromagnetic

[a] Iordachescu and Quintino (2008), Robert and Messler (2004).

not form until it touches the weld pool; this mode of arc is a so-called short arc. The arc mode changes to a globular arc when the current is increased so that a small electromagnetic force is generated (Wang et al. 2004). In a globular arc, the diameter of the droplet is bigger than the electrode and the droplet is formed by the gravitational force. By further increasing the current, the type of arc changes to a projected spray arc, then a streaming arc, and finally a rotating arc (Li and Zhang 2007). The different types of arcs can be shown in diagrams of arc voltage and current.

As an illustration of the influence of current, voltage, and shielding gas composition, Iordachescu and Quintino in an IIW meeting in 2003 classified arc types on the basis of 'natural transfer modes'. Today, however, due to the use of more developed controllers, natural transfer modes are no longer used as often (Iordachescu and Quintino 2008). Figure 8 from Ponomarev's study shows arc type as a function of current, voltage, and shielding gas (Ponomarev et al. 2003).

The transition current has been an important topic in the type of arc in GMA welding. It sets the limit between globular and spray arc and determines the working conditions of the welding process, as suggested by Ponomarev et al. (2003) in Figure 8. According to Iordachescu and Quintino (2008), there could be a second transition current between short arc and globular arc, as illustrated in Figure 9. The aim of the suggestion is to cover both normal spray and projected spray.

In addition to a second transition current line, the study by Iordachescu and Quintino (2008) suggested a new transfer mode classification of the arc in GMAW as a function of the current, voltage, and shielding gas: short circuiting, globular drop, globular repelled, drop spray, streaming, and rotating transfer modes. Figure 9 illustrates this classification of arcs in GMAW (Iordachescu and Quintino 2008). The figure shows the controlled, fundamental, and transfer modes in the same diagram, and each part is separated by transition current zones. The first transition current separates the controlled and fundamental modes, and the second transition current separates the spray and globular fundamental group areas. In addition, the mode of arc changes with increasing welding current and arc voltage. The figure shows that the electric current in short arc transfer is lower than in other types of arcs and that rotating transfer needs a high current.

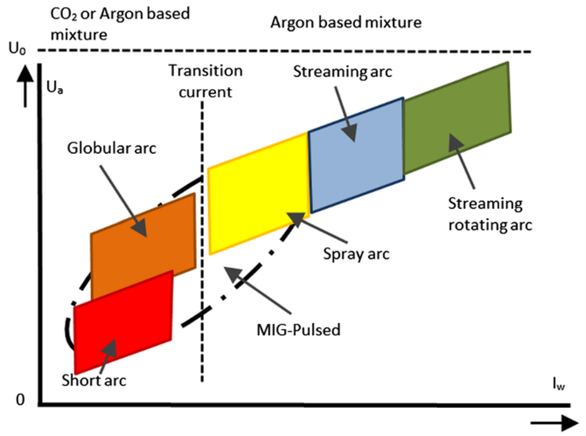

Figure 8 **IIW classification of metal transfer depicted in an arc voltage and welding current diagram (Ponomarev et al. 2003).**

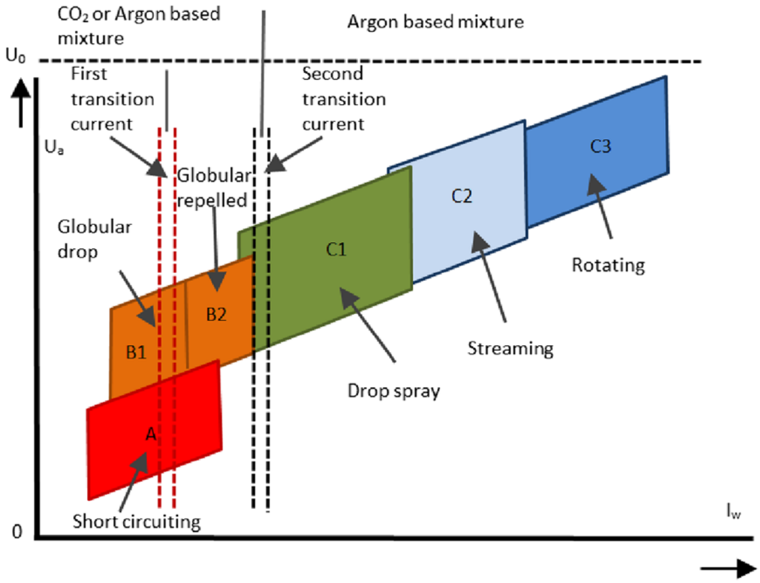

Figure 9 Fundamental transfer modes. U (I) diagram based on the classification by Iordachescu and Quintino (2008).

Table 3 shows an arc type transfer mode from the DIN standards classification in GMA welding (Iordachescu and Quintino 2008). Droplet size and metal transfer mode are also named for each type of arc. Knowing the type of arc and the related transfer mode is mitigated if their related application is ignored. The importance of their corresponding applications rises with the development of new heat-sensitive metal (Matusiak and Pfeifer 2011).

Comparison of different arc types: benefits and weaknesses

A comparison of the types of welding arc is given in this section. The welding arc list consists of natural and controlled types. Table 4 presents a comparative table of key properties of the arc types. Depending on the arc type and arc properties, the table indicates the performance in the industrial application. It can be observed that traditional control arc exhibit weaker arc stability and consequently low performance in term of weld quality. In addition, the operation is not possible in all position except for short arc. The controlled arc exhibits higher deposition rate and better stability. As a consequence of the stability increases, the productivity is greater. The cost saving is the highest, but the equipment are a little more expensive. The level of spatter generated is higher with uncontrolled globular arc; however, the control short arc can achieve virtually free spatter welding. The heat input is minimized with controlled short arc, but higher deposition rate arc requires sufficient heat input. The control focuses on limiting unexpected short circuiting arc, the operation is stable, and the saving cost is significantly improves. Weakness of globular arc can be successfully reduced by buried arc control, the penetration is greater, and spatter is suppressed. Pulse control is the most stable arc with the higher range of current; therefore, a thicker section can be welded and wider range of metal.

Applications of different arc types

A proper selection of an arc type can reduce the risk of weld flaws and improve productivity. In this section, arc type applications are discussed. The discussion starts with natural arc, then followed by controlled arc. The discussion is based on the comparative feature from Table 4 regarding their application, and Table 5 presents the arc type and their applications.

Short arc

A short arc is suited to applications that require low heat input, and it allows the joining of thin materials and sheet

Table 3 Classification of metal transfer in GMA welding in DIN standards (Iordachescu and Quintino 2008)

Types of arc	DIN symbol	Droplet size	Metal transfer
Dip transfer arc	k	Fine	Only in short circuit, regular
Intermediate arc	ü	Fine to coarse	Partly in short circuit, partly short circuit free, irregular
Spray arc	s	Fine to superfine	Short circuit free, regular
Globular transfer arc	i	Coarse	Irregular in short circuit, partly short circuit free
Pulsed arc	p	Adjustable	Short circuit free, regular

Table 4 Comparison of different welding arcs[a]

Properties	Arc type							
	Short arc	**Globular arc**	**Spray arc**	**Pulsed arc**	**High-intensity arc (rotation arc, rapid melt, rapid arc)**	**Short arc controlled (CMT, STT, Cold Arc, CP, WiseFusion, etc.)**	**Globular arc controlled (Buried arc)**	**Spray arc controlled (rapid arc, forced arc, Wise penetration, etc.)**
Spatter	Medium	High	Low	Minimal	High	Free	Minimal	Low
Quality of weld	Weak	Weak	Excellent	Excellent	Excellent	Excellent	Good	Excellent
Heat input	Low	High	High	Low	Medium to high	Low	High	Low
Current level	Low to medium	Low to medium	Medium	Low to medium	High	Low	High	Medium to high
Deposition rate	High	High	High	Medium	High	High	Medium	High
Welding speed	Medium	High	High	High	Medium	High	High	High
Arc stability	good	Weak	Excellent	Excellent	Good	Good to excellent	Good	Excellent
Productivity	Weak	Good	Excellent	Excellent	Good	Excellent	Excellent	Good
Saving cost	Weak	Weak	Excellent	Excellent	Excellent	Excellent	Excellent	Excellent
Penetration	Excellent	Weak	Excellent	Good	Good	Good	Excellent	Excellent
Needs of welder skill	Low	Low	High	Low	High	Medium	Low	High
All position welding	Yes	No	No	Yes	No	Yes	No	Yes

[a] Saunders (1997), Lyttle and Praxair (1990), Bolmsjo et al. (2001), Kielhorn et al. (2001), Aoki et al. (2003), Kang et al. (2003). Kasikci (2003), Kou (2003), Naidu et al. (2003), Althouse et al. (2004), Laren (2004), Robert and Messler (2004), Wang et al. (2004), Stol et al. (2006), Yang et al. (2009), Jeffus and Bower (2010), Matusiak and Pfeifer (2011), Suzuki (2012).

metals in any position. It is a good choice when distortion of the construction needs to be minimized. It is suitable for grooved welds as the root pass or for filling the gaps of joints, as well as for the root pass of open groove joints and plate groove welds. The short arc mode is widely used in the pipe industry and very applicable to root pass welds in pipes. It can be utilized with carbon steel with 100% carbon dioxide shielding gas or a blend of a maximum of 25% CO_2 and a balance of argon. The short arc mode is also applicable to low carbon steel, low alloy steel, and stainless steel with thicknesses between 0.5 and 2.6 mm. However, it is unable to perform welding of aluminium (Deruntz 2003). Although, conventional short arc is used in many applications, its use is limited by high potential excessive spatter generation, fume generation, lack of fusion, lower gap bridgability, and arc instability (Hermans and Ouden 1999; Jenkins et al. 2005). The poor performance of conventional short arc results from the limited ability of the power source to control every sequence of the short circuiting metal transfer mode (Lyttle and Praxair 1990; Althouse et al. 2004; Laren 2004; Goecke 2005a, b; Jeffus and Bower 2010). As a consequence of this limitation, conventional short arc is being progressively replaced by controlled short arc in root-pass sheet metal welding.

Globular arc

The globular arc mode has few applications due to its many deficiencies. Because of the size of the drop (bigger than the electrode diameter), it may unexpectedly touch the weld pool and cause a short circuit. The arc root is highly mobile, so the arc forces tend to move the droplet in an irregular manner, which causes a high level of spatter and weld instability. In addition, the molten metal is not accelerated towards the weld pool, leading to a shallow and broad weld bead. The large droplets are detached at low frequencies (<10 Hz) resulting in low productivity. Consequently, global arc mode is limited to low-quality welded joints welded in a flat welding position or vertical down position (Kou 2003; Xu and Wu 2007). The most suitable application for a globular arc is welding of thin materials at a very low current range. Although it can also be used with a higher current, this is not efficient. It is suitable for GMAW on steel (Althouse et al. 2004; Jeffus and Bower 2010).

Spray arc

Spray arc is required for thicker section than short arc. It is very suitable when a high deposition rate is needed and when deep penetration is required for welding of massive base materials that can tolerate high heat input. The large weld pool makes vertical or overhead position welding difficult, especially in the case of plain carbon steel and stainless steels. For joining steels, the transition current can be varied more than when welding aluminium alloys. A spray arc can be used with almost all common alloys containing aluminium and also nickel alloys, copper alloys, stainless steels, magnesium, and carbon steels (Lyttle and Praxair 1990; Althouse et al. 2004; Robert and Messler 2004; Goecke 2005a, b; Jeffus and Bower 2010). Despite the advantages of conventional spray arc, odd arc instabilities and disordered metal transfer have restricted its adoption. In spray arc mode, the current and voltage are almost

Table 5 Welding arc and applications

Type of arc	Metal	Metal thickness	Joint type	Welding system	Applications	Limitations
Short arc	Ferrous	0.5 and 2.6 mm	Lap joint	Manual	Pipe industries for root pass	High spatter and fume generation
			Butt joint		All positions	Thin section only
			Fillet joint			Not for Aluminium
Globular arc	Ferrous	3 mm and above	Lap joint	Manual	Low-quality weld	Low frequency (<10 Hz)
			Butt joint		Flat and horizontal fillet	High level of spatter and fume
			Fillet joint			Low current range
Spray arc	Ferrous	5 mm and above	Fillet and groove	Manual and automation	Flat position, horizontal position, vertical, and overhead	High spatter and fume generation
	- Non ferrous				Fill passes	Thick section only
						Not suitable for heat sensitive metal
						Restricted shielding gas
Controlled short circuiting arc	Ferrous	0.3 mm and above	Lap joint	Manual and automation	All position	More expensive equipment
	Non-ferrous		Butt joint		Root pass	Digital power source
	Dissimilar		Fillet weld		Transportation industry	
Controlled globular arc	Ferrous	3 mm and above	Lap joint	Automation	All positions	Relatively high current and voltage
			Butt joint		To reduce spatter in conventional globular	Higher burn through potential
			Fillet joint			
Controlled spray arc	Ferrous	1.5 mm and above	Larger joint type application	Manual and Automation	All positions	More expensive equipment
	Non-ferrous				Fill and cover passes	Higher arc energy
	Dissimilar				Root pass	Restricted shielding gas
					Large-industry application	
High-power arc	Ferrous	3 mm and above	Larger joint type application	Automation	All positions	Limited for combination of the welding parameters
	Non-ferrous				Shipbuilding	Risk of arc instability
	Dissimilar				Machine construction	Requires suitable power source
					Steel structure	

steady, which leads to random droplet size and frequency (Hutt and Lucas 1982). Therefore, high fume, spatter, and heat input are generated. As a result of insufficient control, the weld quality can be adversely affected. It should also be noted that the argon-based shielding gas used to achieve spray arc is more expensive than CO_2. In view of these drawbacks, spray arc is unsuitable for aluminium, structural steel, coated steel, and high-strength steels.

Controlled short circuiting arc

These types of arc belong to the category of waveform-controlled modes. The droplet detachment during short circuiting is controlled so as to reduce spatter and fume generation and improve productivity (Stava 1993; Goecke 2005a, b; Huisman 2000). These arcs are commercially marketed under different trade market names: Cold Metal transfer (CMT): (FRONIUS International GmbH), ColdArc: (EWM Hightec Welding GmbH), Surface Tension Transfer (STT): (Lincoln Electric), Cold Process (CP): (CLOOS), FastRoot (KEMPPI), Regulated Metal Deposition (RMD): (Miller Electric Mfg), etc. Pépe et al. (2011) investigated the efficiency of controlled GMAW. The results revealed for STT, fast root and CMT an efficiency of around 85%. Controlled short arc can be used in almost all welding positions, with almost all kinds of metallic materials, and with different thicknesses. Controlled short arc is applicable to joining thin sheets, joining zinc-coated and non-coated stainless steel metal sheets, and joining aluminium alloys. Welding of very thin metal sheets made of carbon steel, high alloy steel, low alloy steels, and aluminium is also possible

(Deruntz 2003). Nowadays, the thicknesses of materials used in the car industry are becoming lower than 0.3 mm and the GMAW process with short arc is no longer suitable. Further applications of controlled short arc are GMAW robot welding and brazing for ultra-light gauge sheets in both manual and automatic modes in any position. Dissimilar materials can be welded, such as aluminium and steel, steel and magnesium, and also magnesium alloys (Rosado et al. 2008; Srinivasan and Balasubramanian 2011; Matusiak and Pfeifer 2011). Although the control of short arc gives more flexibility of applications, it requires advanced power source and sometimes special designed torches.

Controlled globular arc

In this mode, the arc is used at the range of the globular arc current but with short arc length. This enables the arc to work under the weld pool surface (a so-called 'buried arc') and take advantage of the arc pressure of the shielded CO_2 to trap spatter. According to Nishiguchi et al. (1975), the buried arc welding technique is capable of achieving higher welding speeds and filler metal deposition rates than a globular arc. Weld speed can reach 2,540 mm/min and clean-up is minimal (Lienert et al. 2011). Stol et al. (2006) studied the use of buried arc GMAW for seam welds. The buried arc approach has great potential for use in the automotive, railroad, and marine industries for welding subassemblies. An example application is welding of edges and sides of aluminium parts as an alternative to GMAW. Controlled globular arc mode can be used for fillet or seam welds in lap or T-joints and square groove butt joints. It is suitable for the mechanized welding of thin section material at high speeds and can be used in fully mechanized or automatic gas metal arc welding. It is also used in the welding of pipe cylinders. A buried arc can be used in car applications in butt welding for the body and semi-automatic welding for the frame and body (Kielhorn et al. 2001; Aoki et al. 2003; Kah et al. 2013).

Controlled spray arc

In order to control heat input and reduce spatter generation and fumes, power sources have been developed with the ability to release one drop for a sequence of arc and pulsed time. The arc uses direct current (e.g. pulsed GMAW) or alternative current (e.g. AC-GMAW) with different current waveforms. A pulsed arc can be used in all welding positions and with all base material thicknesses in both manual and automatic welding systems. Out of position welding is also possible due to the lower than average current level. Because of the low heat input, this mode is suitable for filling gaps. It is widely used in the GMAW of aluminium (Kah et al. 2012). The method is suitable for welding all standard and high performance grades of stainless steel when nickel base or stainless steel filler metals are used. High alloy steels can also be welded by pulsed arc. Super austenitic stainless steel exhibits better mechanical and metallurgical properties with optimized parameters in GMA welding compare to conventional spray (Sathiya et al. 2012). Pulsed arc welding has applications in the shipbuilding industry, for example, out of position welding of high strength low alloy base materials in ship hull fabrication. The advantages of pulsed arc in shipbuilding are that its electrode efficiency is higher compared to flux-core arc welding (FCAW), and it can deliver lower hydrogen weld deposits (Lyttle and Praxair 1990; Knopp and Lorenz 2002; Althouse et al. 2004; Laren 2004; Ueyama et al. 2005; Lebedev 2010; Torbati et al. 2011; Kah et al. 2013).

Higher-power arc

Stream and rotating metal transfer occur at higher power ranges. The rotation of the molten metal is the result of longer electrode stick out (25 to 35 mm) and higher current and voltage, which cause stream metal to deflect out of its symmetry axis and start to rotate under magnetic forces. Although butt welding is the most typical application of rotating arc mode welding, a rotating arc can also be used in narrow gap welding. Heavy thick plates can be welded using this method. Due to the flexibility, efficiency, and productivity of this mode, it can be used in the manufacturing of large and heavy structural parts (Church and Imaizumi 1990). Although the process is reported by Church and Imaizumi (1990) as requiring quaternary shielding (He-Ni-CO_2 and O_2), which allows very limited tolerance, Suban and Tusek (2003) indicated that a binary shielding gas (argon and CO_2) could produce satisfactory results with optimized welding parameters. Full exploitation of its potential is in completely mechanized procedures (Masseti 2010). Large-scale bridge parts, heavy machinery, shipbuilding, and heavy cylindrical structures are some examples of its applications. A new development of the rotating arc, rotation that is not due to the magnetic effect but to special small rotating torches, makes it possible to apply a rotating arc mode to fillet welding in shipbuilding, bridges, etc. The mode is also suitable for low carbon steel plates (Iwata et al. 2009a, b; Yang et al. 2009; Christensen et al. 2005).

Conclusions

The study reviewed and collated information related to the welding arc. Heat flux, current density, shear stress, and arc pressure are four major factors that should be considered when ascertaining the influence of arc plasma on the weld pool. From the study, the following insights are of importance:

Only 20% of the heat is carried by conduction from hot gases, and 80% remains with the electric current in the weld pool. The range of the arc temperature varies between 5,000 and 30,000 K, depending on the precise nature of the plasma and the amount of current flowing through it. Arc current and arc voltage are the two most important factors determining the arc characteristics affecting the weld quality.

AWS has classified welding arcs into three main categories: short, globular, and spray arcs. Other variations of arcs mentioned in this study are pulsed, cold, rotating, buried, and rapid arcs. A stable arc has three main features: a constant shape of droplets, constant length of arc, and low amount of spatter.

When welding with a short arc, there can be a lack of fusion and the deposition rate is low. Consequently, the main applications of this mode are limited to carbon steel, low carbon steel, low alloy steel, and stainless steel with a thickness of 0.5 to 2.6 mm.

Spray arc is limited to flat and horizontal welding positions, but almost all materials can be welded using this mode. Globular arc is rarely used in industry because it produces a high level of spatter.

Control of the arc has significantly improved the control of heat input, spatter, and fume generation. Pulsed arc, has demonstrated 75% undercutting, a 10% to 30% reduction of the cycle time due to higher welding speed, and an ability to weld metals such as aluminium and high-strength steel. New variants of pulsed arc, such as double pulsed and variable polarity pulsed arc, enable melting efficiency control and bridge ability.

Controlled short arc is applicable for thinner cross sections and is less harmful to zinc coated metal. It has been found to provide 85% arc efficiency. The arc is more stable, is virtually spatter free, and generates fewer fumes than conventional short arc.

In future research aimed at improving understanding of arc phenomena, the distributions of velocity, pressure, temperature, current density, and the magnetic field of plasma arcs could be calculated using computational fluid dynamics (CFD). Improved two- or three-dimensional modelling of different types of welding arc would enhance understanding of welding results. Furthermore, predictability of the effects of different arcs on different materials and applications would be improved.

Competing interests

The authors declare that they have no competing interests.

Authors' contributions

The main authors PK and HL have prepared the paper and the other authors RS, JM, MP have checked and provided significant suggestions to improve the paper. All authors read and approved the final manuscript.

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