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A scientific application oriented classification for metal transfer modes in GMA welding

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ABSTRACT

In this work, metal transfer in solid wire GMA welding was studied. Several experiments with different combinations of gas-wire-parameters were carried out to observe metal transfer and to characterize the various transfer modes. A laser shadograph system with synchronized electrical signals and high speed filming were used. New modes were observed and their particular characteristics described for completeness. A classification for metal transfer, oriented to scientific personnel (researchers, scholars and students), is proposed, in which the modes are independent of the type of shielding gas or welding power source.

1. Introduction

One of the most characteristic phenomena of gas metal arc welding (GMAW or MIG/MAG) is molten droplets transferring across the arc from the wire electrode to the liquid weld pool. Different transfer behavior, referred to as "droplet transfer mode", can be observed Influenced by, e.g., growth time, dimension and detachment frequency. The main parameters affecting droplet generation may be considered to be wire composition and diameter, shielding gas composition and electrical polarity, as well as arc length and welding current level. This, in turn, may be on-line controlled to improve process features. Controlled metal transfer modes have been a significant development in the last decade, due to enhanced power source control features using the welding parameters to generate unique types of droplet transfer.

Acknowledging the importance of this subject, researchers worldwide, and in particular members of the International Institute of Welding (IIW), strove for a logical classification. The first classification (IIW, 1976), established more than 30 years ago, is still used by several researchers. Despite its merit, this classification neither encompasses recent controlled transfer types nor the metal transfer modes recognizable only when applying sophisticated measurement technologies.

During the last decade, some leading researchers have contributed to the elaboration of a more comprehensive classification. Norrish (2003) proposed to extend the above mentioned classification adding two more groups of modes namely *Controlled Transfer Modes* and *Extended Operating Modes*. He also proposed to consider the transfer modes mentioned in the former classification as the *Natural Transfer Modes*. Norrish's intention was to encompass transfers modes that happen in novel processes. However Lucas et al. (2005) 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), furnishing those labels with superscripts ^{N} and ^{C}, depending whether the metal transfer is natural or it is generated by a control system (e.g., A^{c} is a controlled short-circuiting transfer). Iordachescu and Quintino (2008) proposed a similar approach using alphanumeric labels (A, B1, B2, C1, C2 and C3). In spite of a good intention, both labeling approaches look somewhat confusing. Izutani et al. (2006) presented a comprehensive description of the metal transfer modes, yet partially polemic, and suggested some improvements for the classification in force.

From those works, it is clear to have in the welding community two approaches. Some authors look to simplify the classification, while the others strive for a more comprehensive and detailed, i.e., towards a more "scientific" one. The first approach is focused on allowing the broadest welding community to apply the classification for practical situations, aiming mainly to meet industrial needs, while not covering the entire range of metal transfer modes. The latter approach strives to cover the intricate physical aspects of metal transfer. Although both approaches may be equally justified, the IIW, as reported by Norrish (2009), has adopted the simplified

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classification, which does not always meet researchers' requirements, in particular when describing complex process interactions. For example, two different transfer modes in which the droplets are transferred by different mechanisms, yet using similar welding parameters, would have the same classification under the 'simplified' classification. This classification also neglects cyclical changes in transfer modes. Thus, the initial objective of this work was to carry out a detailed study of metal transfer in GMA welding with the intention of identifying all types of metal transfer, including the novel Controlled Transfer Modes produced by the new power sources. The final intention is a 'scientific application oriented' classification in order that all types of metal transfer can be classified.

2. Experimental procedures

A series of experiments was carried out with the aim of reproducing parameters that would lead to differing types of metal transfer in GMA welding. Different types of metal transfer were produced by varying the composition of the shielding gas and wire, as well as the current and voltage levels.

The main methodological approach was a system for metal transfer visualization, as used by Lin et al. (2001), among others. The objective was to achieve a shadow projected by the various elements (contact tube, electrode, drops, weld pool and plate) on the lens of a camera, a technique known as backlighting. The experimental rig was set in accordance with Fig. 1. A high-speed digital camera working at 2000 fps and a 632.2 nm He–Ne laser were used. To enable the arc to be also seen, optical filters of different intensity were employed. Balsamo et al. (2000) synchronized the electric signals with the film frames to correlate the variations in voltage and current with the formation and detachment of the drops.

3. Observation of the metal transfer characteristics

3.1. The natural metal transfer modes

Modes such as "short-circuit", "globular" and "spray", occur as a function of the set electrical parameters, i.e., current and voltage. The modes and variations of these modes, e.g., contact and free flight transfer, are listed in Table 1. The physical forces affecting natural GMA welding droplet transfer are not to be dealt with in detail in this work, but, for the sake of completeness to define their physical character, they are also listed in Table 1. It is common to all modes in Table 1 to occur "naturally", that is, they are not forced by additional electrical parameter or wire feeding control. However, more than one single transfer mode may be referred to either as "contact" or "free flight" category.

Heald et al. (1994) showed that the groups, and respective transfer modes, are related to welding process parameters and shielding gas types, usually represented through diagrams, which are often referred to as "transfer mode maps". Scotti (2000) presented different versions for them, having similar content, yet using different approaches, as illustrated in Fig. 2. Welding voltage (U_a) plotted against current (I_w) is the most conventional way of representing a transfer map. A second version would use "arc length" (L_a), or, more precisely, the "arc gap extension", instead of voltage, since arc gap is considered to describe the influence on transfer behavior more realistically. As there is a proportional relationship between "U_a" or "L_a" and "I_w", the drawings can take slight differences in shape. The fields for "Repelled globular" and "Explosive" modes are not shown in the maps, because they are overlapped by the globular and spray projected fields. It is also widely accepted that these modes are governed by shielding gas and filler wire grades, rather than by welding current and voltage (arc length). It is also important to mention intercession areas, existing between adjacent transfer mode fields (transition areas) and characterized by eventual transfer instabilities.

To be classified as a pure *short-circuiting* mode, there must be a contact (short-circuit) between the droplet under formation and the pool before drop detachment. During the short-circuit periods, the arc extinguishes. As shown in Fig. 3, a liquid metal bridge is formed and then grows as the droplet is sucked into the molten pool (by surface tension). As the short-circuit current at this stage is not very pronounced, there is insufficient electromagnetic force to constrict (pinch effect) the metal bridge. Then, owing to a reduced electrical resistance in the bridging, the current increases progressively, heating the wire by Joule effect (absence of anodic heating at this moment). The bridge is necked out by the combined effect of the surface tension and the progressive electromagnetic forces (pinch effect), the latter as a consequence of the increased current at the final stage.

Although there is an equilibrium between the wire melting rate and its feeding speed during the short-circuiting mode, just after the end of the short-circuit, the first parameter becomes higher than the latter one (due to the still increased post short-circuit current), leading to a limited increase of the arc length. At this point, there is also an accelerated formation of a new droplet at the tip of the electrode wire. As the current subsequently falls, the rate of the wire melting matches the wire feed speed during the following few milliseconds. Afterwards, as the current intensity becomes smaller, the wire feeding rate exceeds the wire melting rate, causing the wire to gradually approach the weld pool.

As a characteristic of metal transfer, it is important to point out that, during the end of the "open arc period", there is a continuous, yet slow, droplet approach towards the weld pool (the melting rate at this period is low and so is the droplet formation speed). Another inherent phenomenon is an oscillation of both the droplet and the weld pool, leading to arc length variations (from 1 to 2 mm). If this droplet-pool oscillation (each at its own frequencies, according to different molten masses, viscosity, etc.) is towards each other, consistent short-circuit conditions take place. On the other hand, if the oscillations are chaotically out of phase, slight contacts between the wire electrode and the weld pool may occur, a phenomenon called "incidental short-circuiting". No metal transfer, but spatter generation may result.

Bridging transfer, also belonging to the "*contact transfer group*", happens when the wire is subject to only low short-circuit current during the contact drop-pool. The surface tension becomes the driving force for metal transfer, reducing the importance of the pinch effect on droplet detachment. Neither droplet repulsion (low pool and droplet oscillation) nor spatter generation is observed with bridging transfer and smooth weld pool behavior leads to a uniform bead appearance. Usually generated with a constant current power source characteristic and/or very high inductance levels, this transfer mode has a restricted range of parameters (arc voltage, welding current and welding speed). However, once set, the transfer mode can be properly used for, e.g., joining thin sheet metals.

The *forced short-circuiting transfer mode*, is characterized by parameter settings for a short arc with a very high wire feed speed (over 10–12 m/min), to produce a welding current as high as 250–350 A. As the transfer is governed by a strong electromagnetic (pinch) force, the droplets are of small size (no time to reach larger volume) with a high transfer rate minimizing the surface tension effect. There is a high level of spatter.

Globular metal transfer is encountered when operating the welding process with low to moderate current and moderate to high voltage (i.e., extended arc lengths), thereby avoiding short-circuits. Large droplets, reaching diameters of 1.5–3 times the wire diameter, and very low droplet transfer rates, in the order of 1–10 droplets per second, characterize this transfer mode. Being retained at the wire tip during its growth by surface tension and vapor jet reaction

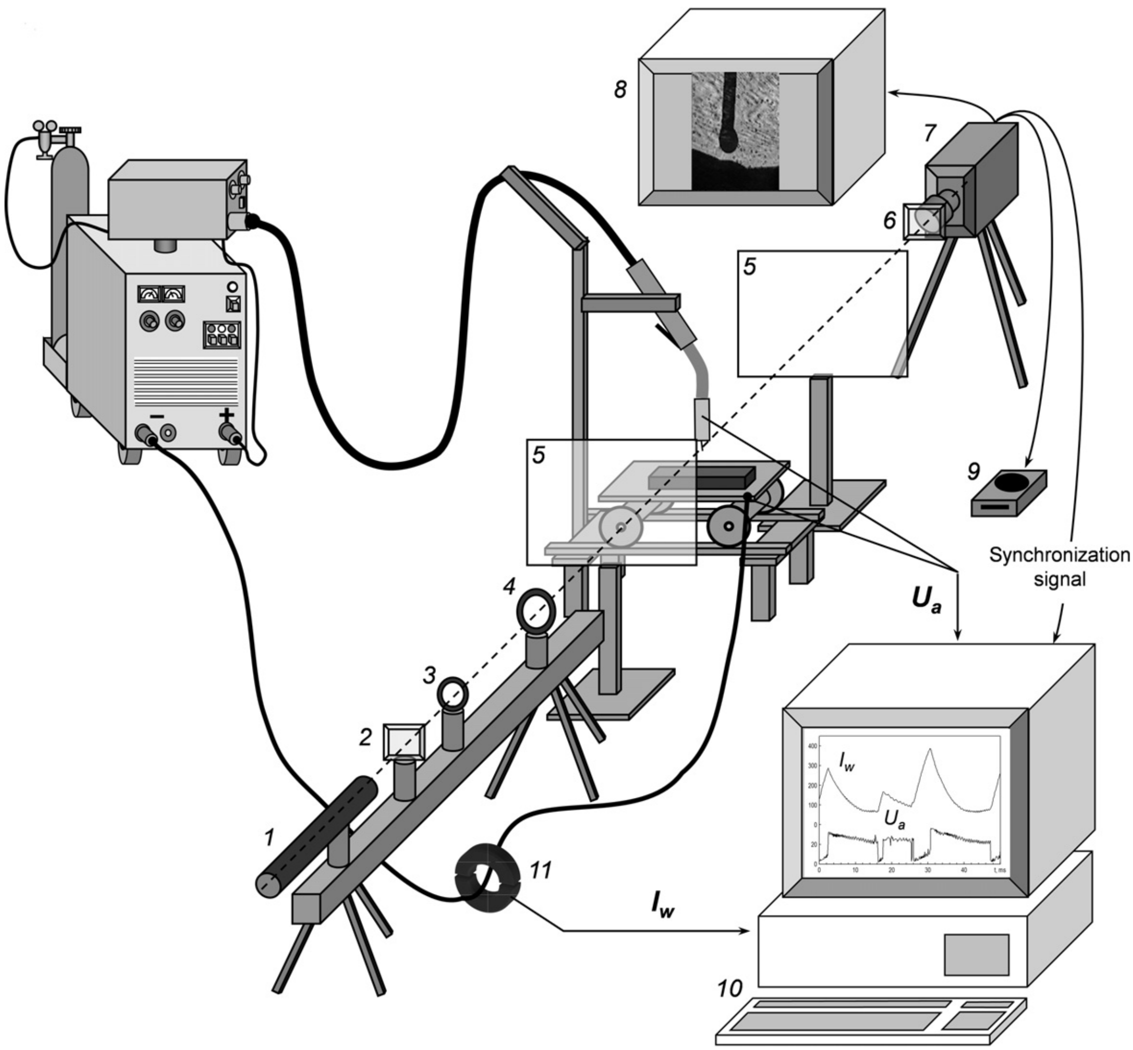


Fig. 1. Details of the optical laser system used for metal transfer visualization. 1, light source (laser); 2, neutral filters; 3, divergent lens; 4, convergent lens; 5, protection glass; 6, band-pass and neutral filters; 7, high-speed video camera; 8, monitor; 9, image recording unit; 10, computer; 11, current hall probe.

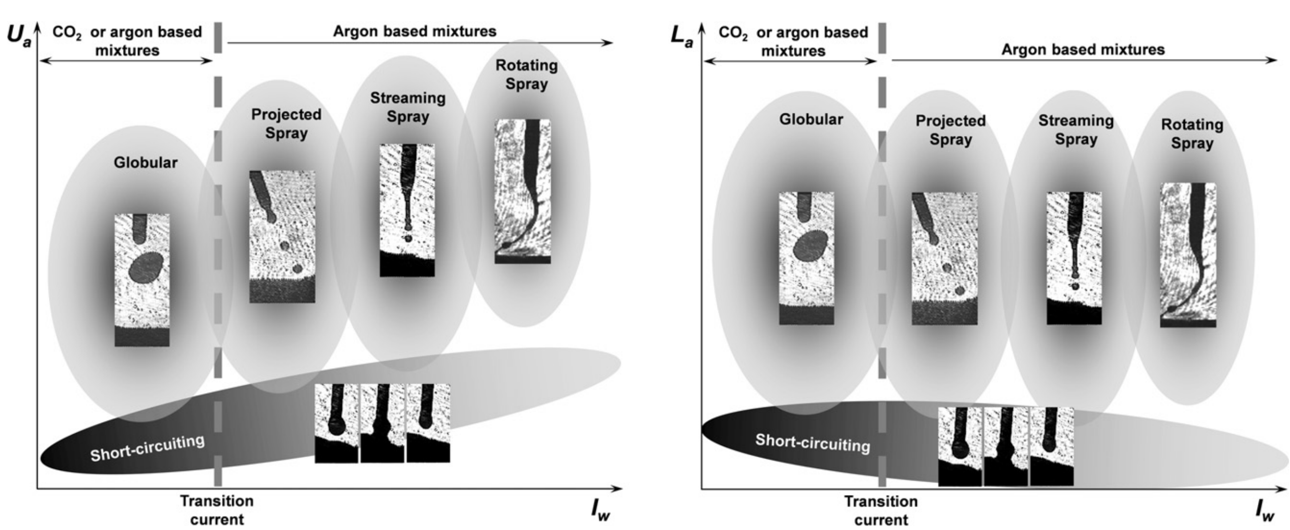
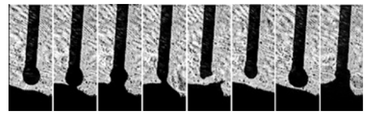
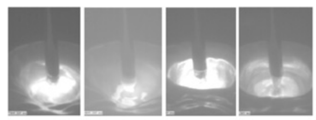
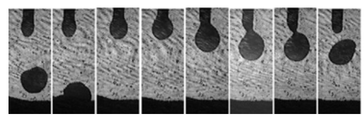
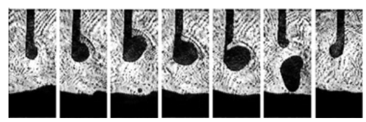
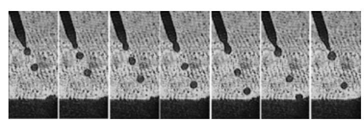
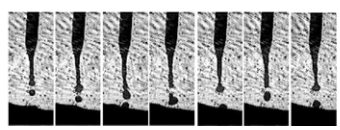
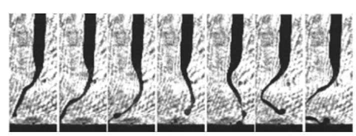
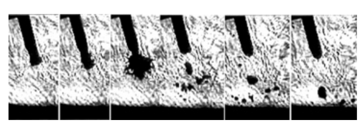


Fig. 2. Schematic maps of the main natural metal transfer modes occurring in GMA welding as a function of the welding current (I_w), represented by either the welding voltage setting (on the left) or by the arc length (on the right).

Table 1
GMA welding natural metal transfer modes.

Group of modes	Transfer mode	Appearance	Main governing force (effect)
Contact transfer	Short-circuiting		Surface tension and electromagnetic pinch effect
	Bridging		Surface tension
	Forced short-circuiting	 (*)	Strongly pronounced electromagnetic pinch effect
Free-flight transfer	Globular		Gravitational force
	Repelled globular		Gravitational force and repelling forces
	Projected spray		Electromagnetic force
	Streaming spray		Electromagnetic force
	Rotating spray		Electromagnetic force
	Explosive		Electromagnetic force and chemical reactions

(*) This sequence of photographs was kindly provided by Fronius, through Mr. Stephan Egerland and Mr. Josef Artelsmair.

force, the droplet is detached finally when gravity and aerodynamic forces exceed the former (a critical droplet diameter is reached). Electromagnetic forces are negligible due to the lower current. When the droplet starts growing, the neck formed at the interface between the wire end and the droplet presents a larger area than the arc coupling area (due to the lower current), which also makes the pinch effect act backwards. As the droplet grows, the neck elongates up to a point in which the arc coupling area overcomes the neck area, when the pinch effect now helps the transfer. Thus, the electromagnetic force, even on a small scale, contributes to droplet growth. This helps to explain why the droplet size does not change very much inside the operational current envelope for globular transfer. Droplet size, shape and behavior depend on the shielding gas type, filler material diameter and composition and the welding current level.

"*Repelled globular*" droplet detachment may arise from globular transfer when applying certain welding conditions (some types of shielding gas, DCEN polarity, etc.). The arc spots become constricted and concentrated underneath the droplet, creating repulsive forces (the pinch effect acting backwards and the metal vaporization reaction). It is believed that excessive vapor can also be formed in the pool by some shielding gases (especially CO_2 rich gases). The large droplet formed just over the weld pool results in a high pressure acting on the droplet due to a small escape area. The forces repel the droplet from the wire axis, causing it to grow further and towards one side. Droplet transfer occurs when gravity and aerodynamic forces exceed the repelling arc forces.

Based on the dominant nature of gravitational forces, the globular transfer modes, both pure and repelled, are known to have very limited suitability for welding in positions other than the flat. When welding, e.g., in the vertical position, some droplets are simply lost, since their mass and volume impede a proper transfer from the wire to the weld pool. As in short-circuit transfer, the wire feed and fusion rate are approximately the same. But, during the droplet growing phase, the arc length becomes progressively smaller and (when using constant voltage power source and most

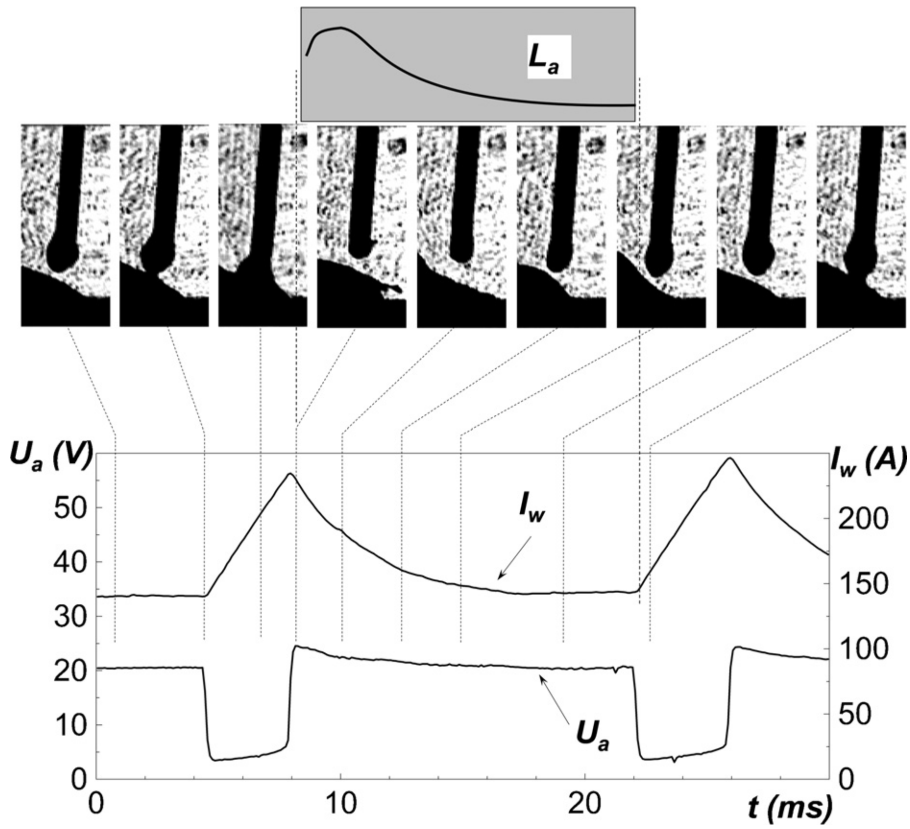


Fig. 3. Typical traces of arc length (L_a), arc voltage (U_a) and welding current (I_w) during GMAW short-circuiting transfer.

shielding gases) the current increases proportionally. The fusion rate increases more than the wire feed speed (not as much as in short-circuit, since, in this case, the current rise is less) and the drop grows in all directions, including up the wire. It means that at first the electrode does not approach the welding pool but the droplet does. When detachment starts (necking due to gravity force, the current gradually reduces (in response to the higher electrical resistance), making the fusion rate smaller than the wire feed rate. With necking, the slight pinch effect assists the gravity force to overcome the surface tension retaining action and to detach the droplet.

Projected spray is characterized by small droplets (close to the electrode diameter) transferring from the electrode tip to the weld pool at a rate of hundreds per second, without short-circuiting the pool. Very regular, yet high, heat transfer to the pool is obtained and no significant amounts of spatter are observed. However, projected spray transfer can only be used in the flat position, because of the large volume of the molten metal in the weld pool. A prerequisite for projected spray is both high voltage (long arc) and moderate to high current, the latter to exceed the so-called "*transition current*". This threshold is dependent on a great number of parameters, such as filler material, shielding gas composition and electrode extension/diameter. Below the "transition current" and with moderate to high voltage, the transfer is globular. If the current is set above the transition current, the spherical droplets become progressively smaller, correspondingly increasing the transfer rate (characteristically, fine droplets at high rates, with high momentum rate, as demonstrated by Scotti and Rodrigues, 2009). The wire electrode tip becomes a little bit pointed. The radial, compressing, fraction of the electromagnetic force increases dramatically, subjecting the droplet to a strong pinch effect, limiting its volume and size and allowing only a small droplet to be formed. There is very little oscillation of current and the equilibrium of wire feed rate and fusion rate is acceptable. At this level of current, the balance of forces acting in the metal transfer is not only based on the static equilibrium theory, but also upon a combination of forces explained by the pinch instability, as proposed by Allum (1985). Kim and Eager (1991) found that the static force balance theory would give more realistic representation of the globular metal transfer phenomenon if the effect of dynamics of droplet motion at the electrode tip is taken into consideration. In addition, they state that the pinch instability theory is unable to explain the metal transfer at globular and spray projected transfer mode, but the droplet size at the streaming transfer is thought to be determined by the pinch instability.

With a further increase of the welding current, projected spray transforms into "*streaming spray*" transfer. In addition to greater heat produced in the electrode tip, the anodic area needs, to some extent, to increase due to higher current arriving the wire end (the arc climbs the wire surface). As a result, a wire volume above the arc-wire coupling is heated enough to become plastic, resulting in the "*tapered*" shape of the electrode end. Hence, the wire end changes into an almost molten stream towards the weld pool, forming a conic shaped metal column. At the tip, very fine droplets are formed and detached. Electromagnetic forces (acting predominantly in accordance with the pinch instability phenomenon), mentioned in the "projected spray" section, are taken as the governing phenomenon in the metal transfer, leading to a smaller droplet diameter and higher transfer frequency than with projected spray. As long as this tapered end does not touch the pool, there is no spatter. Welding in positions other than the flat one becomes even more difficult.

Beyond "*streaming spray*", the "*rotating spray*" transfer mode takes place, attainable by a further increase in the current level. The wire electrode tapering effect is more pronounced with overheating, resulting in an extended metal filament. Strong electromagnetic forces, caused by the excessively high welding current applied, move the column away from its straight line of flow. The combination of asymmetric radial forces and azimuthal forces results in a spiral motion of the column. The droplets (extremely fine) are detached from the tip of the rotational filament in tangential direction, producing a lot of spatter.

It has been observed that, under some circumstances (certain gas and wire compositions), droplets attached to the electrode tip can eject material in an explosive manner in which small droplets are expelled from the molten part of the electrode tip and transferred to the weld pool. This is thought to be due to chemical reactions (gas–metal) inside the droplet. This transfer mode is named *Explosive transfer* and is usually accompanied by considerable amount of fine spatter.

3.2. Modes resulting from controlling the transfer

Special welding applications (e.g., joining thin sheet metals, welding in the vertical position or requiring low spatter) highlight the physical limitations of "*natural*" transfer modes. These limitations can be overcome by using advanced welding equipment, which allows automatic adjustment and control of the transfer. The resulting transfers can be categorized as "*controlled metal transfer*", but they are in effect natural modes obtained deliberately, either through programming parameter changes or through adaptive control as a response to a parameter variation. The most common examples of controlled metal transfer modes are the "*pulsed transfer*" and the "*controlled contact transfer*".

Commercially applied since the 1960s, the "*pulsed transfer mode*" is a very well-known approach to control the droplets. In *pulsed transfer* a long arc length is used and the welding current is cyclically pulsed from a low value (base current), sufficient, however, to maintain the arc, to a high value (pulse current) and sufficient to form and detach a droplet (a spray-like transfer). For a given pulse current, pulse time is precisely required to lead to one drop detached per pulse, as explained by Kim and Eagar (1993) among others. Ueyama et al. (2005) describe a special pulse mode variant, designated AC (Alternating Current) or VP (Variable Polarity) MIG/MAG welding. During DCEN polarity, a droplet forms on the end of the wire. The droplet is forced across the arc when the current switches to DCEP polarity. Nascimento et al. (2008) explain that the transfer is controlled by the parameter settings at both polarities. Another special controlled pulse mode is double pulsed MIG/MAG welding, in which the high frequency pulsing current controls metal transfer but superimposed low frequency or thermal pulsation is used to control the weld pool (similar to pulsed GTAW).

Controlled contact transfer modes may be considered as a means of improving the regularity of the droplet to weld pool contacts which occur under natural short-circuiting transfer. By reducing the randomness of natural transfer, a "softer" droplet detachment (no spatter and improved weld pool controllability, due to higher thermal regularity), is achieved. To achieve this aim, many researchers, like for instance Stava (1993), suggest to use adaptive control systems for modulating current (control of the voltage signal level throughout each contact stage), while Pickin and Young (2006), similar to other specialists, added wire feeding variations to assist in the breaking of the molten metal bridge breaking. Branded commercial names, such as STT™, CMT™, RMD™, FastRoot™, etc. are related to controlled metal transfer techniques.

The controlled metal transfer modes might be sub-classified in accordance with the main parameter (parameters) subjected to adaptive control, as follows:

- Spray transfer controlled by pulsed current (DC and AC) (the current is automatically adjusted by the machine using an algorithm to form the appropriate pulse and base periods);
- Contact transfer controlled by current (the current is controlled during and/or before the short-circuit stage);
- Contact transfer controlled by current and wire feeding (not only current, but also the feeding of the wire, forward and backwards, is controlled during and/or before the short-circuit stage).

3.3. Modes that happen in an interchangeable way

Ponomarev et al. (2002) show that there is a pattern of transfer which is not widely commented on in the current literature, most likely because the related transfers are difficult to be identified using ordinary laboratory techniques. Moreover, they are easily confused with temporary transfer instability during a setting at a transition operational envelope between two adjacent natural modes. For certain welding conditions, two or more transfer natural-like modes happen in a periodic sequence (without any interference of the operator and/or a control system), such as interchanging of modes. One important characteristic of this transfer is that the following mode is a consequence of the previous one (the variation of current, electrode temperature and/or plasma status due to a transfer mode gives rise to conditions for the following mode to take place). For instance:

- Short-circuiting-projected spray;
- Short-circuiting-streaming spray;
- Globular-projected spray;
- Globular-streaming spray;
- Globular-short-circuiting-streaming spray-globular;
- Others.

Though the instances of these transfer modes may occur between periods of natural modes, they should not be confused with a transition transfer mode, because they are characterized by other fundamentals, such as sequential periodic repeatability (i.e., it is not a phenomenon of occasional natural instability between two modes). This interchangeable metal transfer mode takes place if, and only if, all necessary conditions are present, i.e., a combination of current, arc length, material and diameter of the wire, shielding gas, contact-tube to work distance (*CTWD*) and favorable dynamics (inductance) of the power source. In other words, if there are no favorable conditions between two natural modes, this mode of metal transfer will never happen.

For instance, if the welding current exceeds the globular-spray transition current level, there may be a change in the Natural Transfer Mode (short-circuiting or globular to projected spray or even streaming spray). Shortly thereafter, this current decreases and the transfer mode type coherently returns to the previous one, initiating a new cycle. An example of interchangeable metal transfer mode is shown in Fig. 4.

4. A scientific application oriented metal transfer classification

First of all, it is important to state the terminology used in this work for this classification:

- *Mode* (metal transfer mode) defines a characteristic behavior of a drop under transference in GMA welding, e.g., "*globular*" mode (large drops traveling from the wire tip to the weld pool) or the so-called "*spray*" mode (small droplets traveling consecutively from the wire tip to the weld pool).
- *Group* (group of modes) stands for a number of modes that have similar characteristics.

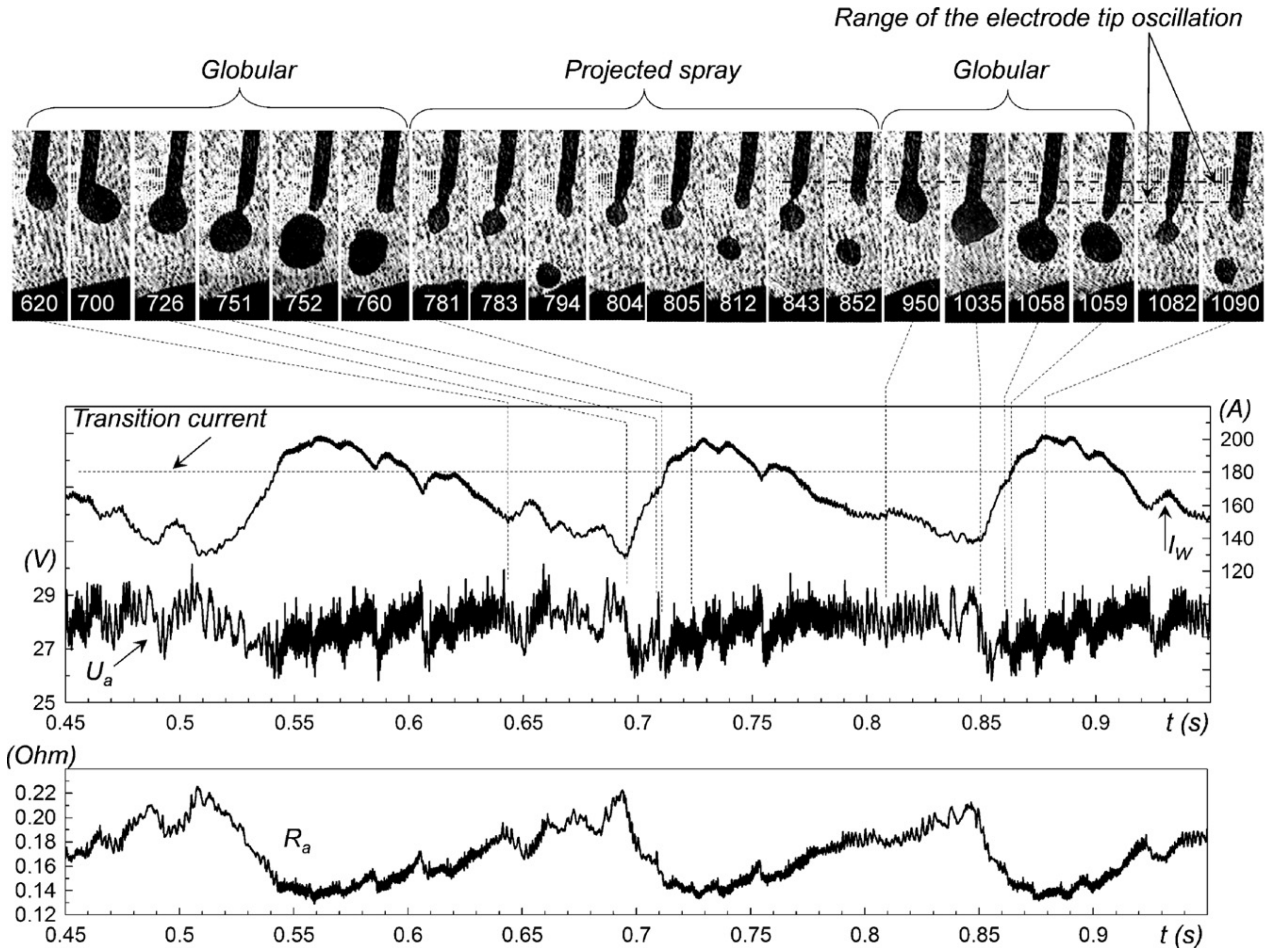


Fig. 4. An example of an interchangeable metal transfer mode of the type "globular-spray": an electronic power source with the constant voltage characteristic; carbon steel wire of 1.0 mm diameter; U_a = 27.9 V; I_w = 166 A; *WFS* = 6.3 m/min; travel speed = 30 cm/min; *CTWD* of 18 mm; shielding gas Ar + 5% O_2 (the current and the arc resistance R_a are mirror symmetrical, being the latter which controls the former).

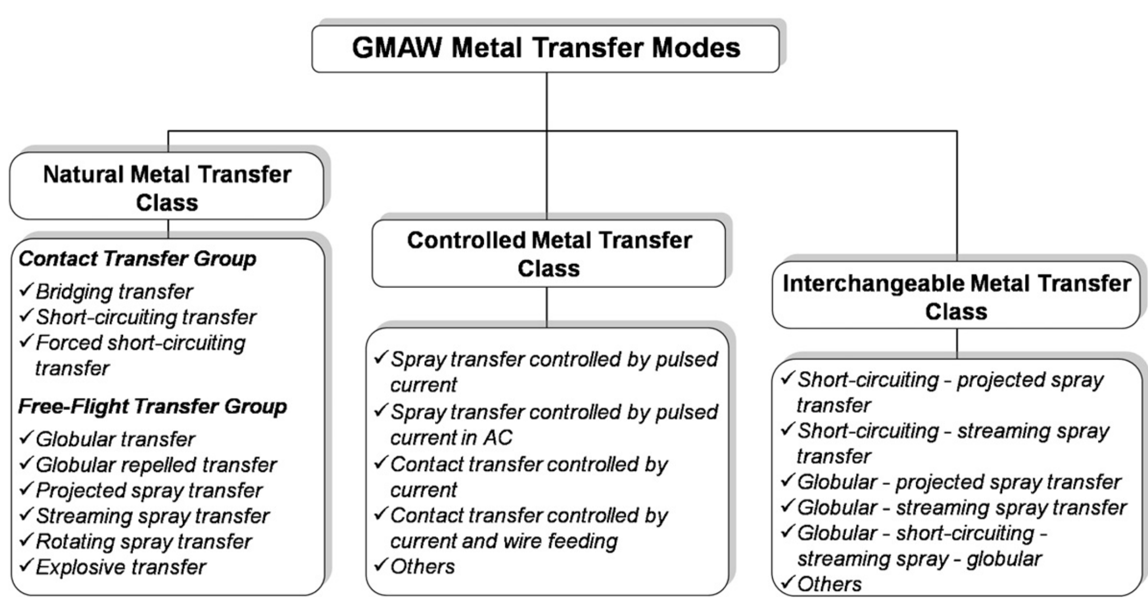


Fig. 5. GMAW metal transfer classification based on hierarchical order (classes, groups and modes).

- *Class* (class of modes) is the highest hierarchical (parental) grouping of modes. A class of mode can be formed by one or more groups.

Members of the IIW have reached a consensus on a simple metal transfer classification which has two classes, namely "*Natural Metal Transfer*" and the "*Controlled Metal Transfer*". In the scientific application oriented classification, a third "*Interchangeable Metal Transfer*" class is included to cover those modes which have periodical changes in the transfer mode provoked by changes in welding parameters (an "autophagic" behavior). The classification oriented to scientific users is summarized in Fig. 5.

The characteristics of the three classes of metal transfer modes are as follows:

The '*Natural Metal Transfer*' class contains those modes that occur without any further adaptive welding parameter control (e.g., arc voltage, welding current, wire feed speed, inductance). Hence, droplet transfer is primarily affected by a resultant physical balance of forces acting upon the droplet. Two different groups can be found within the natural metal transfer class. The first is governed by "*contact*" droplet transfer, while the second shows a "*free-flight*" droplet transfer to the weld pool.

The "*Controlled Metal Transfer*" class consists of "improved" natural modes, for getting better process characteristics, such as spatter minimization, weld geometry control, heat input stabilization and so forth. Hence, the balance of transfer governing forces still prevails but the forces are controlled and/or modified deliberately.

The "*Interchangeable Metal Transfer*" describes a class of modes that occur with two or more Natural Transfer Modes happening in a periodic repetitive sequence, one following the other, as a consequence of the previous one. There is no operator or adaptive control system interference.

5. Conclusions

The proposed scientific application oriented classification for metal transfer modes satisfies the demand for having a systematic method to describe all metal transfer types in GMA welding, including the novel or not easily observed ones.

The terminology for the modes is short and self-describing.

The categorization in metal transfer mode, group of modes and classes of modes avoids specific applications or commercial names since it is based on global characteristics of the metal transfer and on the phenomena taking place.

Unambiguously, this classification facilitates the communication between Researchers and Academics, yet useful for Engineers in the field.

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