Journal of Materials Processing Technology 214 (2014) 2488–2496

Contents lists available at ScienceDirect

Journal of Materials Processing Technology

journal homepage: www.elsevier.com/locate/jmatprotec

Interchangeable metal transfer phenomenon in GMA welding: Features, mechanisms, classification

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ARTICLE INFO

Article history:
Received 7 August 2013
Received in revised form 16 May 2014
Accepted 18 May 2014
Available online 29 May 2014

Keywords:
Welding
GMAW
Metal transfer

ABSTRACT

Metal transfer modes in arc welding processes have previously been classified as Natural or Controlled Metal Transfer. Modern laboratory techniques have helped to establish a new transfer classification mode in GMAW of carbon steels, which has been termed Interchangeable Metal Transfer. In order to characterize the new mode, a series of specimens was welded at different combinations of welding current (wire feed speed), arc voltage and gas composition. Laser backlighting techniques and high speed filming were employed to study metal transfer. The video was synchronized with the welding current and arc voltage signals to aid the understanding of the transfer behaviour. The results showed that this new interchangeable metal transfer class is distinguished from the Natural or Controlled Metal Transfer class because of its unique characteristic of periodical changes in the transfer mode induced by changes in welding parameters (a self-sustained behaviour). The characteristic feature of the interchangeable metal transfer class was shown to comprise of two or more natural transfer modes occurring in a regular repetitive sequence. The metal transfer sequence occurs without interference from the operator or the adaptive control system of the power source. Phenomenological explanations based on arc physics are given to justify the main governing factors for the particular metal transfer characteristics.

1. Introduction

Gas Metal Arc Welding (GMAW) is a widely used process in the metal fabrication industry. Welds are produced by using an arc to melt a wire electrode. Metal from the melting wire is transferred to the joint in the form of droplets that detach from the electrode tip. The performance of this process is governed by the metal transfer mode that is the way in which the metal droplets are detached from the wire electrode and transferred to the weld pool.

Mode (a short for metal transfer mode) defines the characteristic behaviour of the droplets transferring from the wire to the weld pool. For example, the "globular" mode describes large drops being detached from the wire and transferring under gravity to the weld pool whilst the "spray" mode describes small droplets being projected from the wire tip to the weld pool. Group of modes refers to a number of modes that have similar characteristics. Several characteristic transfer modes have been described in current literature. The first classification, established more than 30 years ago by the International Institute of Welding (IIW), as seen in the IIW Doc. XII-636-76 (1976), is still used by several researchers. Despite its merit, this classification is applicable to natural transfer modes only and neither encompasses recent controlled transfer types nor the metal transfer modes recognizable only when using sophisticated measurement techniques. Natural modes are defined here as a mode with transfers not forced by additional electrical parameter or wire feeding control, in contrast to controlled transfer modes, as explained by Scotti et al. (2012) in another publication. Scotti et al. (2012) when using a laser shadograph system with synchronized electrical signals and high speed filming, observed some new modes and described their particular characteristics. These authors proposed a revised classification for metal transfer specifically for use by scientific personnel (researchers, scholars and students). However, there is no one best mode covering all applications as there is a preferred mode for a specific application. As a consequence, a better understanding of the metal transfer phenomenon is important for improvements in the quality and productivity of GMA welding.

Heald et al. (1994) showed that the groups of modes, and respective transfer modes, are related to welding process parameters and shielding gas types, usually represented through diagrams,

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http://dx.doi.org/10.1016/j.jmatprotec.2014.05.022
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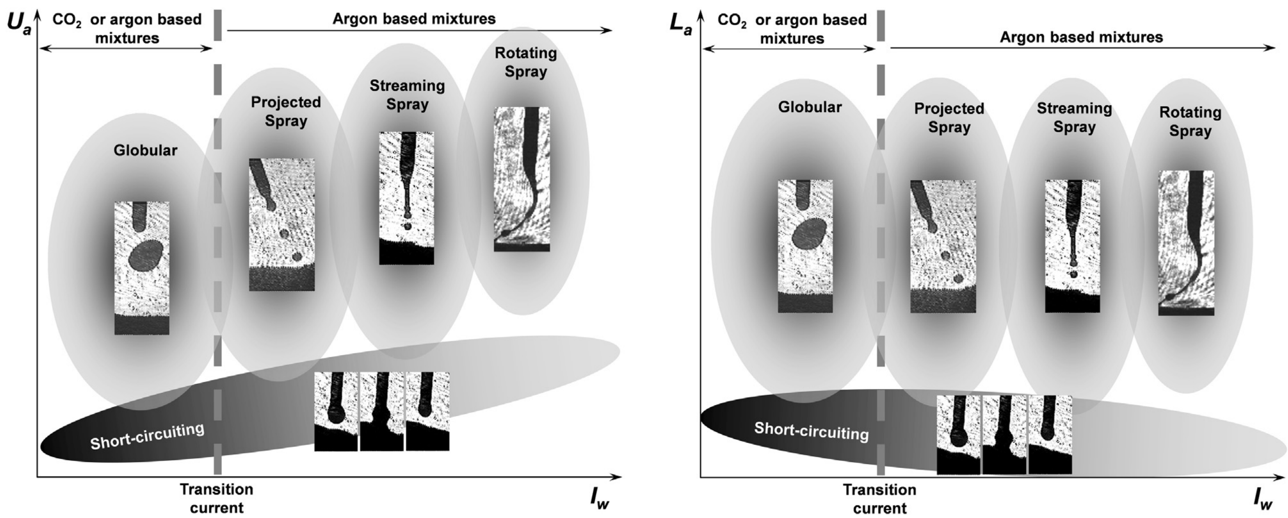

Fig. 1. Schematic maps of the main natural metal transfer modes occurring in GMA welding as a function of the welding current (I_w), represented by either the welding voltage setting, on the left, or the arc length, on the right.
After Scotti et al. (2012).

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. 1. Arc voltage (U_a) plotted against welding 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 arc voltage, since arc gap is considered to describe the influence on transfer behaviour more realistically. It is important to point out that the arc voltage and the arc length are in some cases incorrectly used as synonyms. A direct relationship between the arc length and the arc voltage is widely known (the higher the arc length, the higher the arc voltage), but it is valid only for a given current. When the correlations are established as a function of the current, as the present case, the arc length can be maintained constant for different current values, because they are independent of each other. On the other hand, the voltage will increase as the current is augmented for any arc length, since the voltage is dependent of the current for a given arc length (static characteristics of arcs). As a result, the two drawings can take slight differences in shape.

It is also important to mention the transition zones between adjacent transfer mode fields. In the transition zones, droplet detachment becomes intermediate between, for example, larger droplets of globular transfer and the smaller droplets of the spray transfer modes. This phenomenon can be explained by

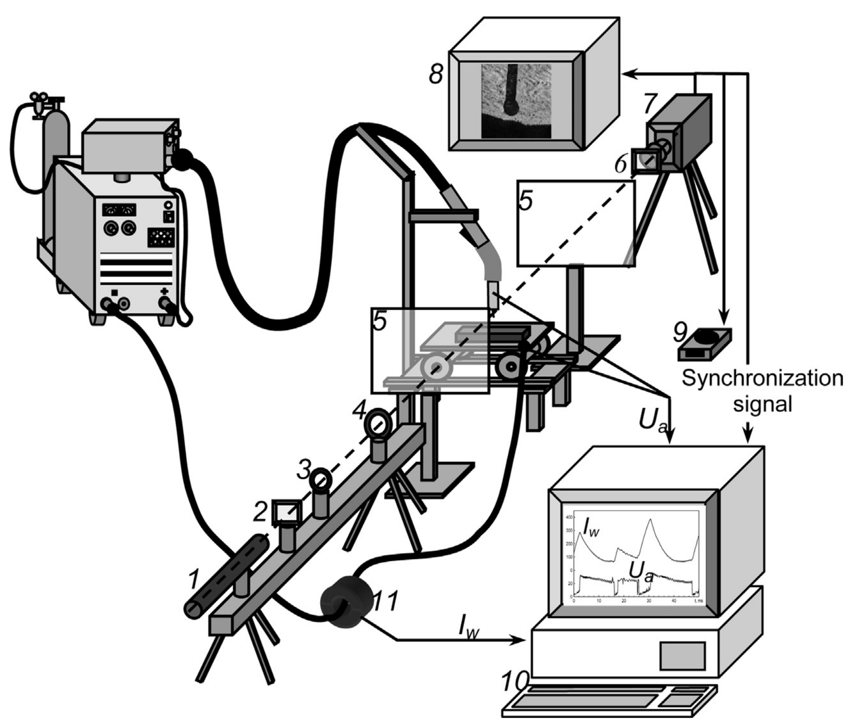

Fig. 2. Details of the optical laser system used for metal transfer visualization. 1, light source (laser); 2, neutral filters; 3, divergent lens; 4, convergent lens; 5, protection glass; 6, band-pass and neutral filters; 7, high-speed video camera; 8, monitor; 9, image recording unit; 10, computer; 11, current hall probe.
After Scotti et al. (2012).

using a model proposed by Watkins et al. (1992), based on the Shaw's model for water droplet growth and detachment. Shaw had observed that droplets flowing from a faucet detached at periodic intervals for low flow rates. As the flow rate increased, the flow rate changed from periodic and predictable to an aperiodic quasi-random pattern of behaviour. Haidar and Lowke (1996) used a theoretical approach for the prediction of the droplet formation. A two-dimensional time-dependent model, accounting for the effects of surface tension, gravity, inertia and magnetic pinch forces in the droplet, was used. The wire feed speed and gas flow rate were also incorporated into the predictions. They also predicted the presence of both small and large droplets (alternately) at the transition zone between globular and spray modes, in agreement with the above-mentioned work.

Similar droplet flow characteristics obtained by the above models were experimentally detected by Clark et al. (1989) and Johnson et al. (1992) in similar conditions (GMAW, Ar-2% O_2, 0.89 mm electrode wire). Johnson et al. observed an electrode extension increase during the detachment of large droplets, justified by a slower melting rate than expected. After a series of small droplet detachments, the electrode extension decreased, since these small droplets melted off faster than the average rate. According to this author, this cycle sometimes repeated itself several times. For example, one or two large droplets may be followed by a series of small droplets but then followed by other one or two large droplets. Madigan et al. (1992) also observed electrode extension changes during metal transfer. Working in the droplet – spray transition zone, with a constant current power source, they observed an electrode extension increase (arc length decrease) just before droplet detachment. These authors considered the electrode extension to be the sum of the solid cylinder and the droplet diameter.

Despite the evidence that there might be some distinctive metal transfer modes happening in the transition zone between two adjacent transfer mode fields, most researchers describe them as transfer mode instability of a chaotic character. However, Scotti (2000) reported that, under certain welding conditions, two or more natural-like transfer modes can happen in a periodic sequence (without any interference of the operator and/or a control system). He also showed in his results that this periodic pattern of changes in the metal transfer mode is not restricted to the transition zones between adjacent fields but may also occur in different combinations. For example, short-circuiting – projected spray, short-circuiting – streaming spray, globular-projected spray, globular-streaming spray, globular-short-circuiting – streaming, spray-globular, etc. were observed. These patterns of transfer have not been widely commented on in the literature, most likely because the related transfers are difficult to identify using ordinary laboratory techniques. Moreover, they are easily confused with temporary transfer instability which may occur for example when operating within a transition operational envelope between two adjacent natural transfer modes.

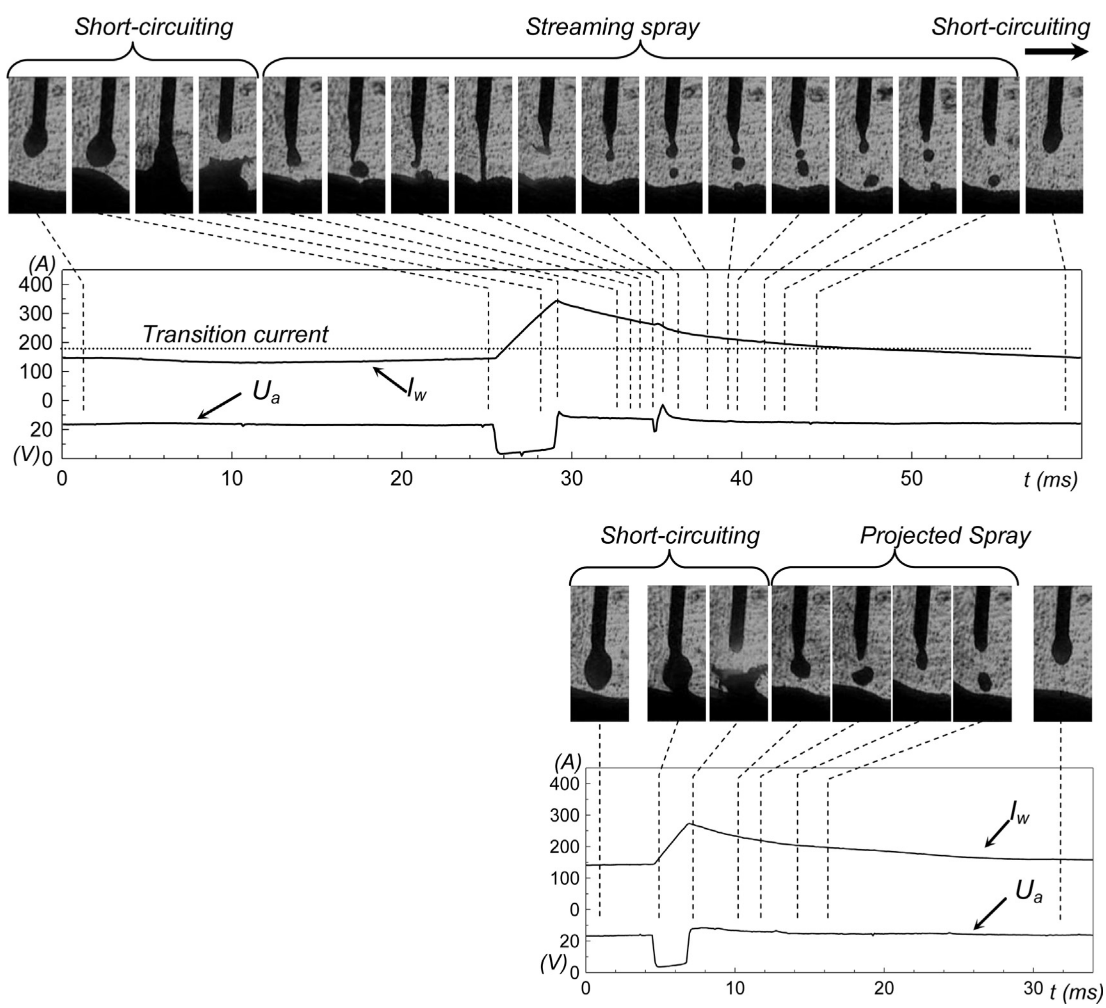

Fig. 3. Examples of an interchangeable metal transfer mode of the type "short-circuiting – spray" (above "streaming" and below "projected" spray) and the correspondent arc voltage (U_a) and welding current (I_w) traces: mean U_a = 23.5 V; mean I_w = 170 A; set *WFS* = 7 m/min; travel speed = 36 cm/min; contact-tube to work distance (*CTWD*) = 18 mm; shielding gas = Ar + 5% O_2.

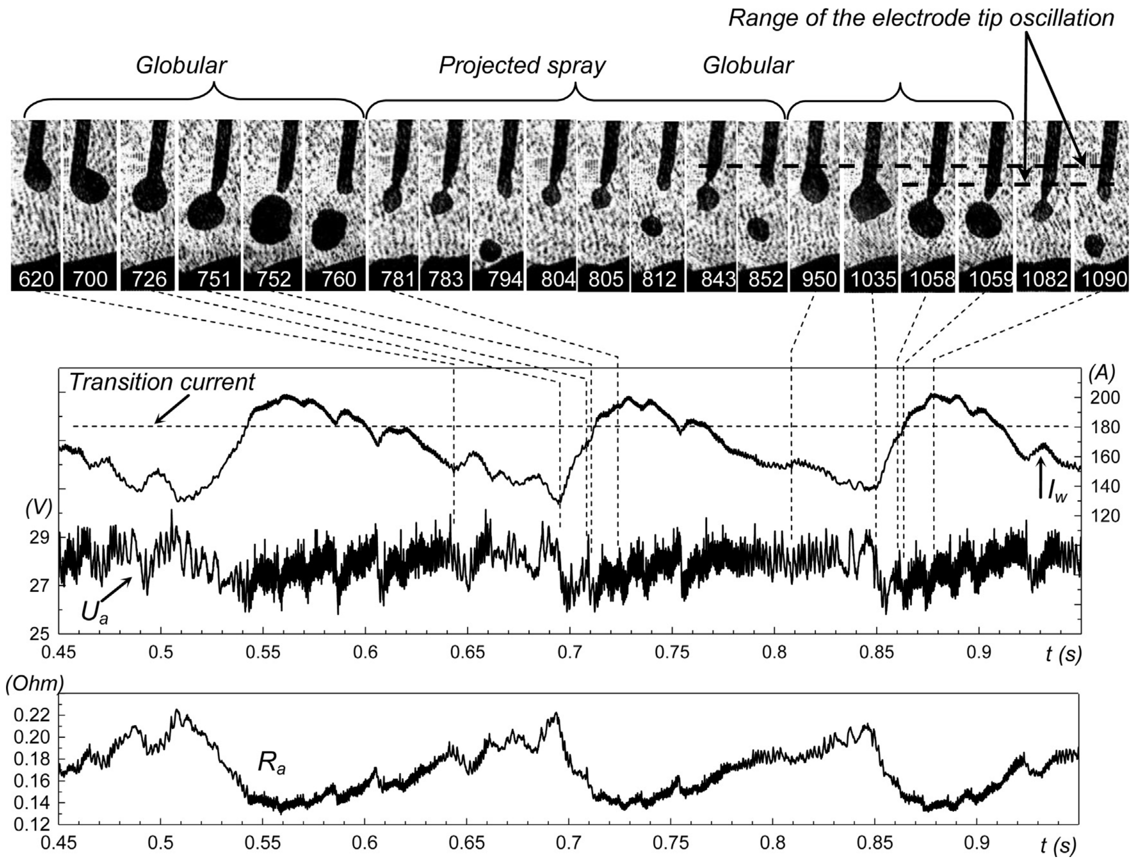

Fig. 4. An example of an interchangeable metal transfer mode of the "globular – spray" type and the correspondent U_a, I_w and instantaneous arc resistance (R_a) traces: mean U_a = 27.9 V; mean I_w = 166 A; *WFS* = 6.3 m/min; travel speed = 30 cm/min; *CTWD* = 18 mm; shielding gas = Ar + 5% O_2.

Despite the above mentioned reports, there is little published information on multi-mode metal transfer. Thus, the objective of this work was to study more consistently the existence of the above mentioned metal transfer class of modes, hereafter referred as "interchangeable metal transfer".

2. Experimental procedure

A series of experiments was carried out with the aim of reproducing welding conditions that would lead to differing modes of interchangeable metal transfer in GMA welding. Bead-on-plate

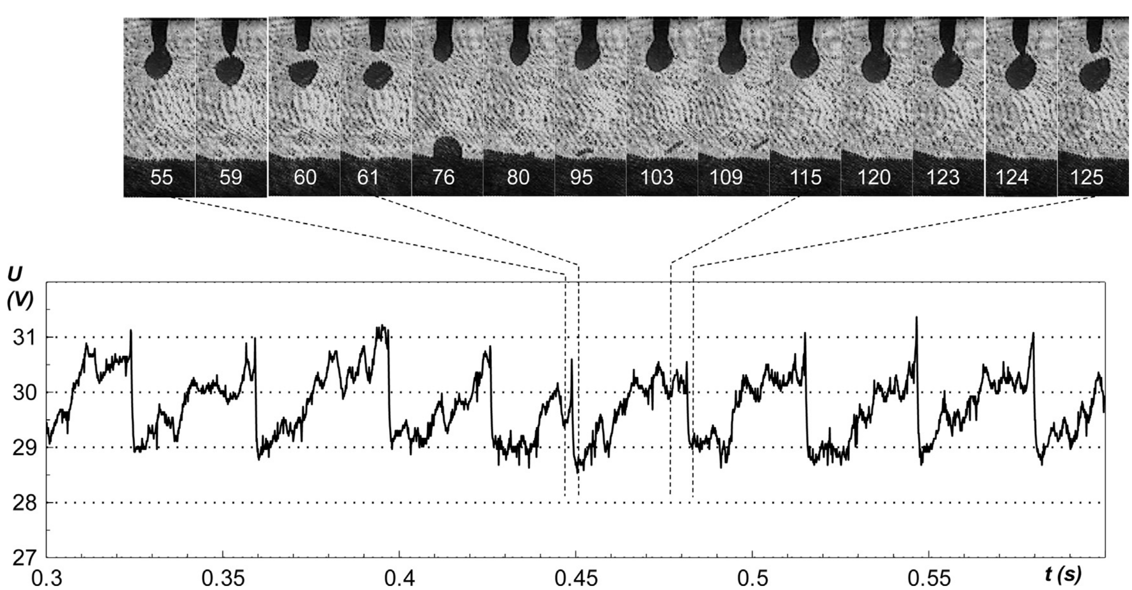

Fig. 5. Voltage trace showing the arc voltage variation as a function of the droplet growing and detachment (globular transfer): I_w = 182 A; *WFS* = 6.7 m/min; *CTWD* = 20 mm; shielding gas = Ar + 2% O_2.
After Scotti et al. (2006).

welds were carried out on carbon steel plates using a 1.0-mm-diameter wire of the AWS ER70S-6 class with DCEP. The approach was to select a different shielding gas (Ar + 2% or 5% O_2) and then set a combination of inductance, welding current and arc voltage to produce the desired droplet transfer mode. An electronic constant voltage output characteristic power source was used in these experiments.

The main methodological approach applied was based on a system for metal transfer visualization as used by Lin et al. (2001) and Bálsamo et al. (2000), among others. The experimental rig was set up as shown in Fig. 2. A shadow of the non-transparent components (contact tube, electrode, metal drops, weld pool and plate) of the arc region was projected onto the lens of a camera, a technique known as backlighting. 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 seen also, optical filters of different intensity were employed. The electric signals were synchronized with the film frames to correlate the variations in arc voltage and welding current with the formation and detachment of the droplets. Synchronization was carried out using a dedicated programme built in a LabView® platform.

3. Analysis of results

Different types of interchangeable metal transfer modes (two or more transfer natural-like modes happening in a periodic sequence) were generated. The characteristics and the reason for the occurrence of each interchangeable metal transfer mode are described and discussed as follows.

3.1. Interchangeable “short-circuiting – spray” mode

The two natural transfer modes during this type of the interchangeable metal transfer are the short-circuiting mode and the streaming/projected spray one, as illustrated in Fig. 3. The welding conditions (arc voltage and welding current instant values) initially favour the natural short-circuiting transfer which includes the droplet growth and short-circuit stages. However, during the post short-circuit period, a higher mean current level leads to a high post short-circuit current, which remains temporarily above the transition current level. Due to this augmented current, the electrode melting rate becomes momentarily higher than the wire feed speed (*WFS*) and the arc length progressively increases. This has the effect of preventing short-circuiting transfer as the process has sufficient time to enable more than one tiny droplet to detach sequentially. With a constant voltage power source, as a longer arc makes the welding current decrease, the electrode melting rate also falls gradually. As electrode melting rate becomes less than the *WFS*, the wire tip returns to approaching the weld pool. The combination of a low current and a short arc reinstates the conditions required for short-circuiting to occur. Normally only one drop is transferred before a new cycle is initiated.

As can also be seen in Fig. 3, switching of the natural metal transfer modes is cyclical which mainly depends on the inductance of the power source (dynamic response of the current, i.e., current rising and falling rates), arc length and the combination of the electrode and the shielding gas which influences the surface tension. The latter determines the transition current level and the others act together to determine the short-circuit duration and indirectly, the short-circuiting current level. These preconditions substantiate the reason for occurrence of the “short-circuiting – spray” interchangeable metal transfer mode.

3.2. Interchangeable “globular – spray” mode

As seen in Fig. 4, globular and spray natural transfer modes are interchanging giving rise to an interchangeable transfer mode. It is considered that the reason for this mode is that when using shielding gas mixtures with less than 12% CO_2 and a carbon steel wire, the electrical resistivity of the droplet becomes higher than that of the arc column. During a globular transfer under such conditions in which the droplet resistivity is greater than the arc column resistivity, the growth of the droplet overcomes the effect of the shortening of the arc regarding the resistance variation. The increase in the summation of the electric resistances consequently reduces progressively the welding current and resulting in a reduction of the wire melting rate. Thus, even though the arc length became shorter, the voltage measured between the contact tip and the work piece increases, as illustrated in Figs. 5 and 6.

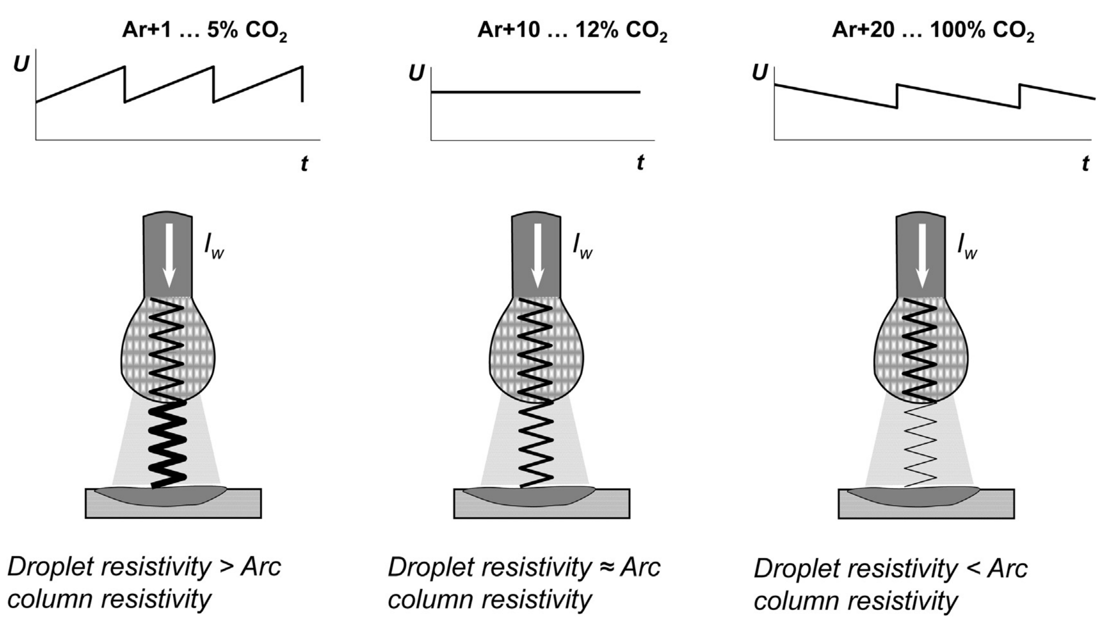

Fig. 6. Schematic illustration of the alteration of the ratio between the droplet and arc column electric resistivities as a function of the CO_2 content in an argon based gas mixture. The droplet and arc column electric resistivities are illustrated by lines, where the thicker line means lower resistivity.
After Scotti and Ponomarev (2008).

Due to a progressive reduction of the electrode melting rate, the electrode tip with a globular droplet attached approaches the weld pool, sometimes causing incipient short-circuits, as shown in Fig. 7. Together with an increase in the electrode extension, the total electric resistance starts to reduce so that the lower resistivity of the wire dominates the resistivity of the arc column and the welding current starts to increase again. Thus, the welding current can reach values above the transition current which is low for these low CO_2 Ar based gas mixtures. This results in a projected (see Fig. 4) or even streaming spray transfer (see Fig. 7). The resulting high electrode melting rate coincident with this high current causes the arc length to increase and the current to reduce. The conditions are now re-established for the globular transfer and a new cycle sets in.

Thus, the reason for a "globular – spray" interchangeable metal transfer mode is a lower specific resistance of the arc column compared to that of the metal droplet, which is conditioned by the use of shielding gas mixtures with less than 12% CO_2.

Then, the question is whether shielding gas mixtures with more than 12% CO_2 could promote or not an interchangeable transfer "globular – spray" as the specific resistance of the arc column is now higher than that of the droplet, as illustrated in Fig. 6. During the globular transfer stage, as long as the droplet is growing and, consequently the arc length is reducing, the arc voltage reduces as well. The reason is that the reduction of the total arc column voltage drop is more significant than the voltage drop in the growing droplet which when using constant voltage power sources, causing a current increase. Then, if, hypothetically, the current exceeds the transition current level, the spray transfer mode could be established followed by an increase of the electrode melting rate and the arc lengthening of the arc. This behaviour could be accompanied by a rise in the arc column resistance, resulting in a reduction in the current. Finally, there might be a re-establishment of the globular transfer mode. A new cycle would be re-established. However, the higher the CO_2 content in a gas mixture, the higher the transition current value becomes, and, thus, it becomes more difficult to be

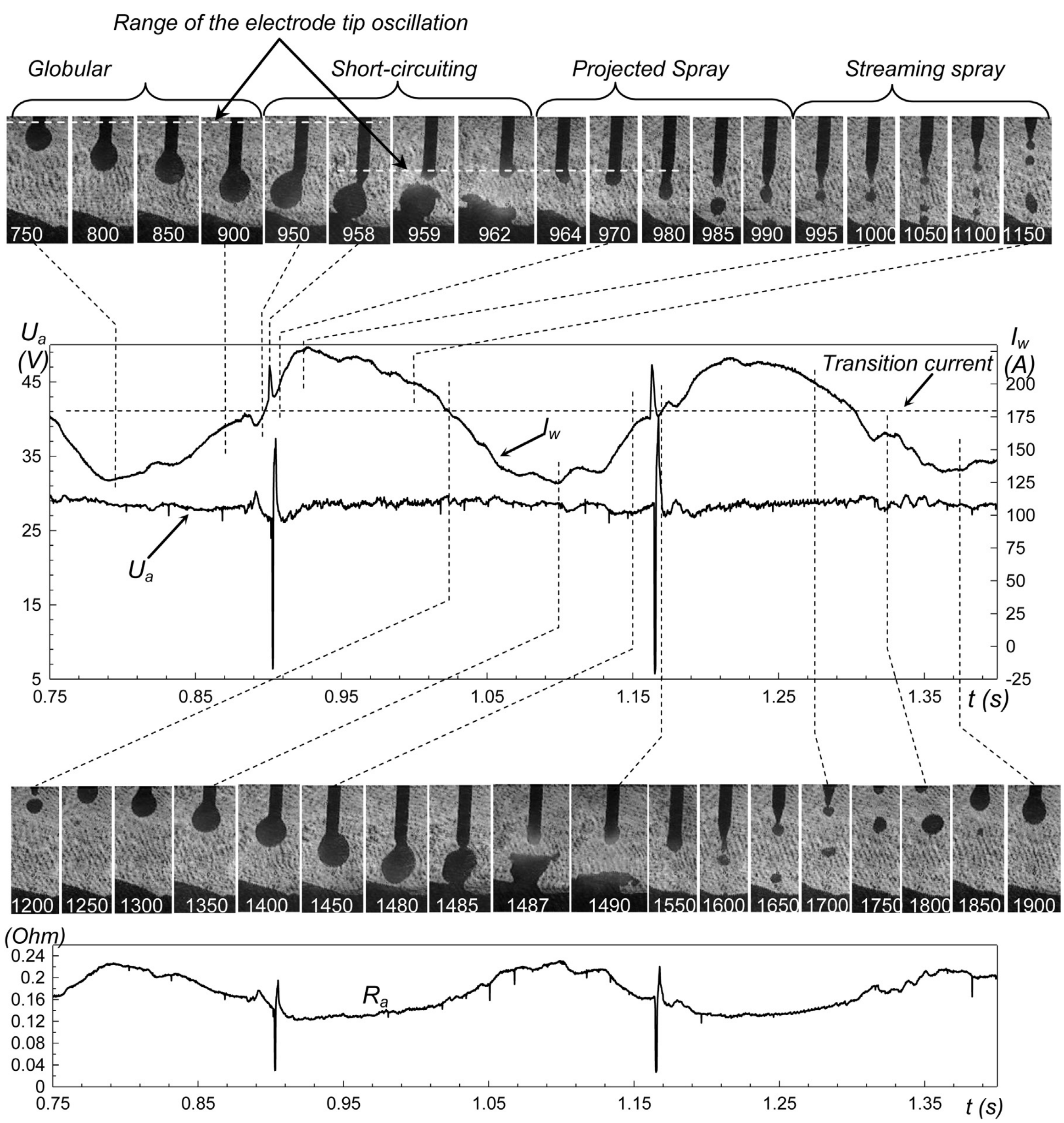

Fig. 7. An example of an interchangeable metal transfer mode of the "globular – streaming spray" type: mean U_a = 28.4 V; mean I_w = 177 A; *WFS* = 6.5 m/min; travel speed = 36 cm/min; *CTWD* = 18 mm; shielding gas = Ar + 2% O2.

exceeded. This is the main reason why the interchangeable metal transfer mode is usually not observed when using CO_2 rich argon based shielding mixtures.

3.3. Interchangeable "globular – short-circuiting – streaming spray" mode

Fig. 8 illustrates the interchangeable mode "globular – short-circuiting – streaming spray". It is considered that, in this case, the conditions described in both Sections 3.1 (high post short-circuiting current) and 3.2 (a lower specific resistance of the arc column and of the wire electrode compared to that of the metal droplet) are acting in combination. There was a gradual reduction of the current between frames 792 and 900, caused by an increase in the growing droplet resistance. Due to the consequent reduction of the electrode melting rate, the electrode tip with a droplet starts to move towards the weld pool, from frames 900 to 1028. Together with an increase in the electrode extension, the total electric resistance starts to reduce and the lower resistivity of the wire now starts to dominate over that of the arc column so that the current increasing again. Although the increment in the current was not sufficient to exceed the globular–spray transition, as there was a short-circuit, the metal transfer mode transition became possible due to a high post short-circuiting current. The reduction of the arc voltage as compared with the case shown in Fig. 7 was one of the favourable conditions for this mode to happen.

3.4. Interchangeable "projected spray – streaming spray" mode

There are certain energy-related conditions which can make the current vary periodically generating the "projected spray – streaming spray" interchangeable metal transfer mode, Fig. 9. The intensive generation of metallic vapour in an arc under streaming spray transfer creates the potential to alter the plasma properties in such a way as to force the current to reduce due to a lower ionization potential and/or heat transfer losses. The transfer would, then, turn into projected spray with less metallic vapour generation, which would make the current increase again, and so on.

An alternative reason for the current starting to reduce at the end of the streaming spray stage is that, when using a constant voltage power supply, a progressively increasing arc length occurs. Vice-versa, during the projected spray transfer, a low current causes the arc to shorten, inducing a current rise and moving the transfer mode transition towards the streaming spray mode. In either case, there is a clear manifestation of the interchangeable metal transfer mode fundamental principles, when variations of conditions due to a previous transfer mode give rise to conditions for the following mode to take place.

4. Classification of metal transfer modes

Although the interchangeable transfer modes occur under welding conditions between those for adjacent natural ones, they should not be confused with a transition transfer mode, because they are characterized by sequential periodic repeatability. It is not a phenomenon of occasional natural instability between two modes. The most important characteristic of Interchangeable transfer is that the following mode is a consequence of the previous one. In particular, the variation of current, electrode temperature and/or plasma status due to a transfer mode

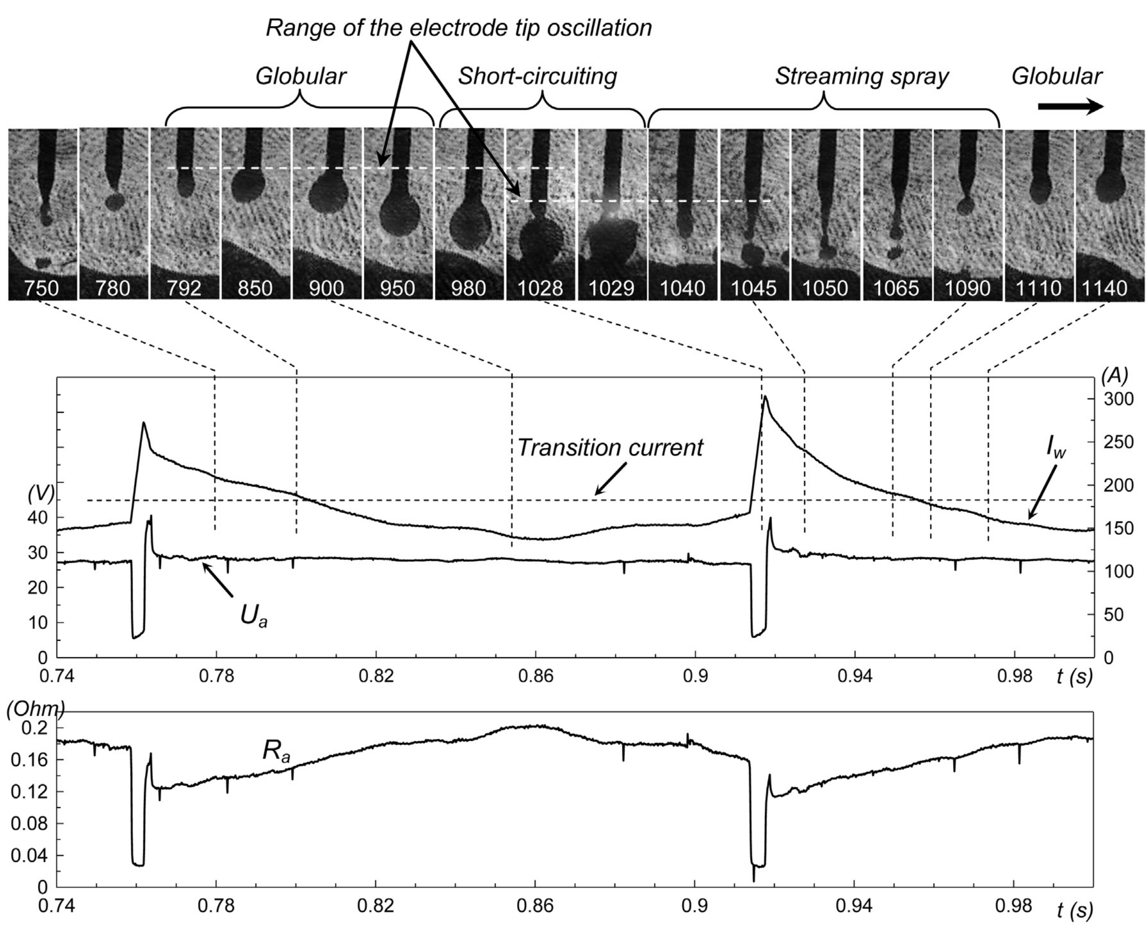

Fig. 8. An example of an interchangeable metal transfer mode of the "globular – short-circuiting – streaming spray" type: mean U_a = 27.5 V; mean I_w = 170 A; *WFS* = 6.5 m/min; travel speed = 36 cm/min; *CTWD* = 18 mm; shielding gas = Ar + 2% O_2.

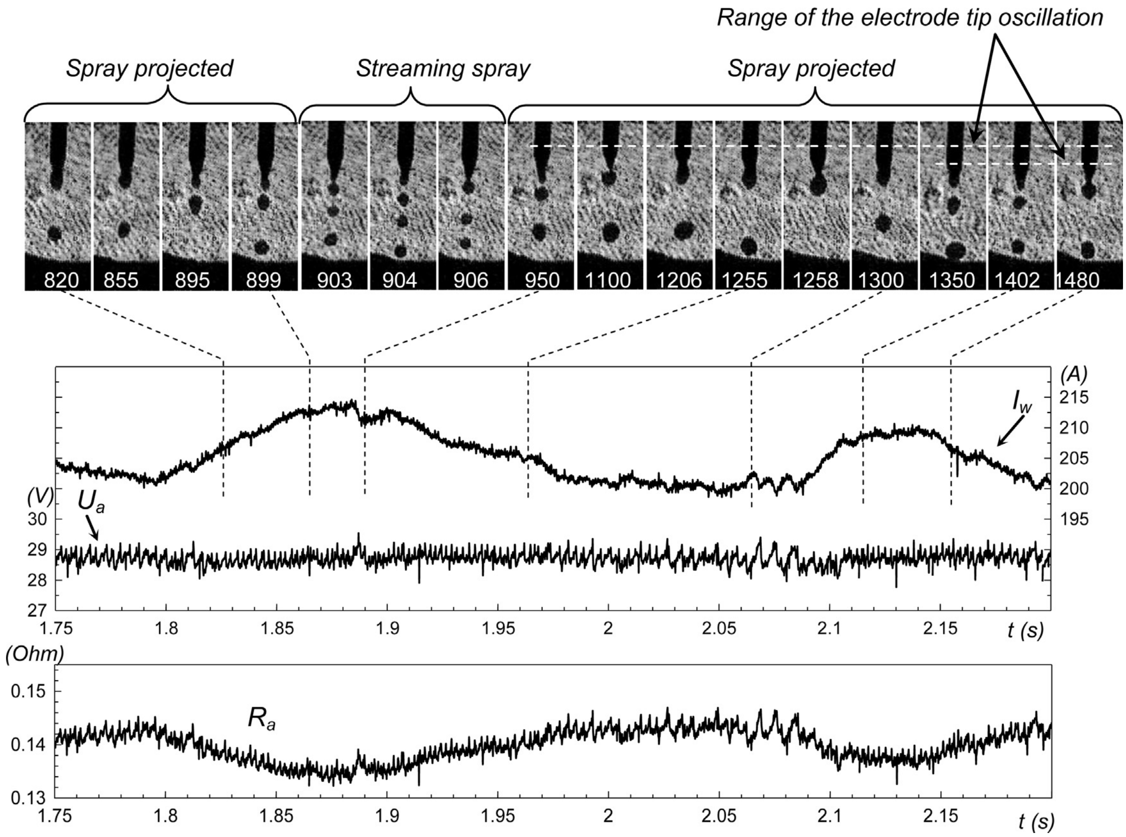

Fig. 9. An example of an interchangeable metal transfer mode of the "spray projected – streaming spray" type: mean U_a = 28.7 V; mean I_w = 207 A; *WFS* = 8.7 m/min; travel speed = 36 cm/min; *CTWD* = 18 mm; shielding gas = Ar + 2% O_2.

gives rise to conditions for the following mode to take place. An interchangeable metal transfer mode takes place only if all the necessary conditions are present, i.e., a combination of welding current, arc length, material and diameter of the wire, shielding gas, contact tube to work distance and favourable dynamics (inductance) of the power source. It is important to note that further research work is still required to establish the ranges for the conditions promoting each of the interchangeable transfer modes.

The *Interchangeable Transfer Mode* cannot be attributed to either *Natural Transfer Modes* because its characteristic sequential periodic changing between two or even more natural transfer modes or to *Controlled Transfer Modes* because there is no in-line or off-line control. These types of transfer mode possess all characteristics of an individual class of modes which has been called *Class of Interchangeable Transfer Modes*, as summarized in Fig. 10.

Interchangeable metal transfer modes are not identifiable by welders and operators, even though characterized by a low

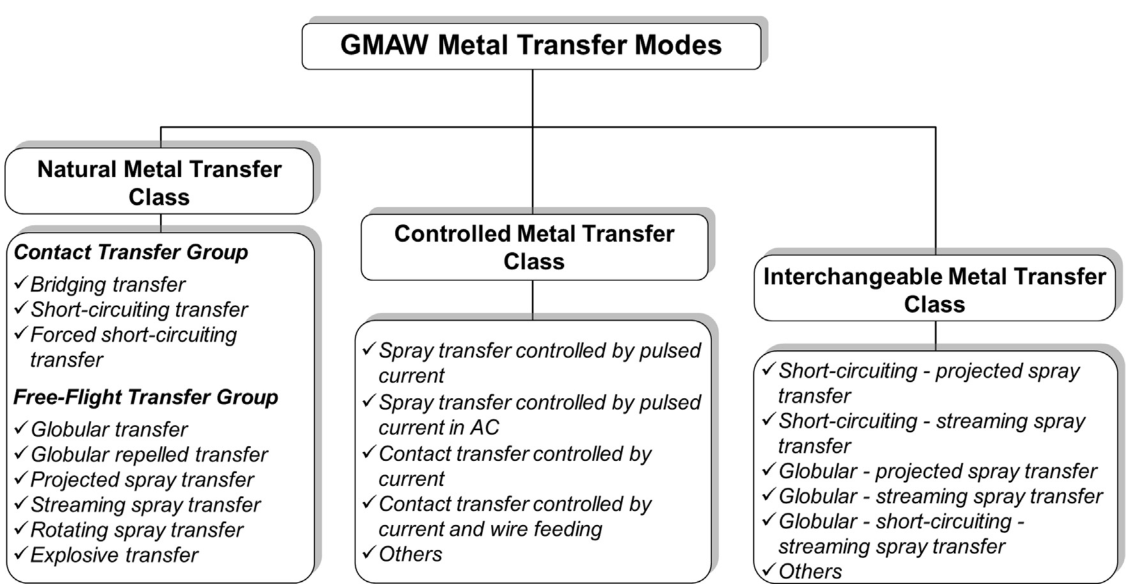

Fig. 10. GMAW Metal Transfer Classification based on hierarchical order: classes, groups and modes.

Described in more details by Scotti et al. (2012).

frequency of metal transfer interchanging (3–5 Hz). If the transfer is interchanging from globular to spray, it is unstable as occurs with a globular transfer. But if it is interchanging from short-circuiting and spray, the welder may not feel the any difference in performance from the normal short-circuiting operation. In fact, modern power source manufactures are trying to develop controlled metal transfers interchanging from, for instance, pulsed transfer to short-circuit transfer, to satisfy special applications.

Including the new "interchangeable metal transfer" class in the overall classification of GMA metal transfer modes for arc welding completes the classification. It is now possible to describe all modes of metal transfer from the simple "Natural Metal Transfer" class to the often quite complex multi-mode type of transfer categorized in the "interchangeable metal transfer" class which has been identified in this study.

5. Conclusions

Modern laboratory techniques, especially high speed video filming synchronized with welding parameters acquisition, brought out evidences that:

- There is a new metal transfer class "interchangeable metal transfer", which with the well known Natural and Controlled Metal Transfer classes completes the classification of metal transfer for GMA welding of carbon steels;
- The interchangeable metal transfer mode is distinguished from the others classes of metal transfer because of its unique characteristic of periodical changes in the transfer mode induced from short temporal changes in welding parameters (a self-sustained behaviour);
- The interchangeable metal transfer mode may comprise 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;
- The interchangeable metal transfer mode can only take place if all the necessary conditions are present, i.e., a combination of welding current, arc length, material and diameter of the wire, shielding gas, contact-tube to work distance and favourable dynamics (inductance) of the power source;
- The interchangeable metal transfer mode does not occur when using shielding gas mixtures with more than 12% CO_2.

Acknowledgements

The authors would like to thank the Brazilian agencies for research and development (CNPq and Fapemig), which have provided the financial backing for the specialized equipment used in this work (high-speed camera, laser back-light system, synchronized frames-electrical signal data loggers).

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