METAL TRANSFER MODES AND RECENT DEVELOPMENTS IN THEIR CONTROL IN THE GMAW PROCESS

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ABSTRACT

The paper reviews the classification of metal transfer in GMAW and the recent developments in metal transfer control. An expanded classification which takes into account the recent developments is proposed.

KEYWORDS

GMAW, Metal Transfer, Controlled Transfer, Pulsed GMAW, Controlled Dip Transfer.

1. Introduction

Gas metal arc welding (GMAW) was introduced in the 1950's but metal transfer from consumable electrodes had been studied since the introduction of the manual metal arc process in the early 1900's. It was initially thought that the filler material vaporised and re-condensed in the weld pool. The advent of relatively high speed cine in 1919 however confirmed that metal was transferred by discrete droplets [1]. Several researchers carried out phenomenological studies of metal transfer in the 1960's using shadowgraph and high speed film framing rates of around 4000 frames per second [2]. These studies revealed that transfer was primarily dependent on current, filler material and shielding gas and resulted in the classification of GMAW transfer modes illustrated in figure 1.

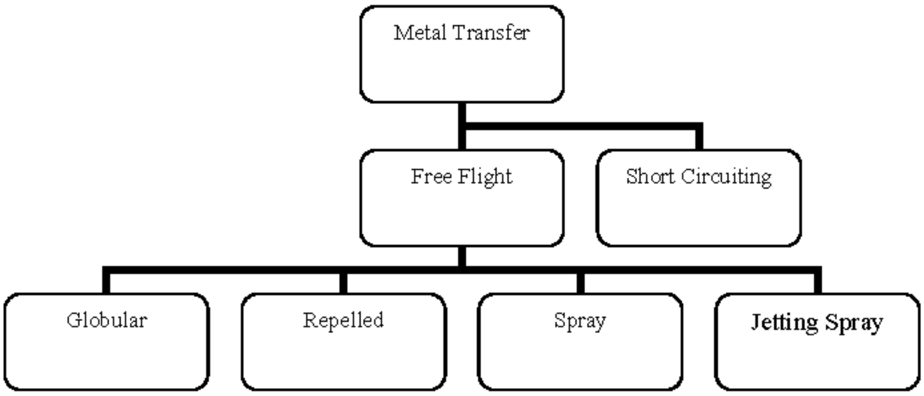

Figure 1. Early classification of metal transfer

The two principal modes were described as *free flight* and *short circuiting* transfer. Short circuiting transfer occurred at low current and low voltage and was a stable mode when ferritic steel wires were operated in a CO_2 shielding gas. In free flight transfer the metal droplet was detached from the end of the filler wire and traveled through the arc to reach the weld pool whereas in short circuiting transfer the tip of the electrode bridged the arc gap during transfer. In the free flight mode several distinct variations were observed; in general as current density increased the transfer changed from large droplets substantially larger in diameter than the filler wire to smaller projected droplets and finally to a very small jet of droplets. Several unstable asymmetric transfer modes were also observed, these included repulsion of large droplets in a low current repelled transfer mode and long ‘whip’ like molten necks at high current. These phenomena were strongly influenced by filler wire and shielding gas and for example for steel wires in CO_2 the free transfer modes were predominately globular or repelled at low current and jetting spray at very high current densities. With many materials in argon the transfer was observed to change from globular to spray when a transition current of around 200 amps[1] was exceeded.

The most useful transfer modes were regarded as:

- Short circuiting transfer for ferritic steels in CO_2 or argon/CO_2 mixtures
- Spray transfer in most materials at currents above 200 amps

The short circuiting mode has been used extensively for joining thin sheet steel and positional welding of thicker sections. Its limitations were the relatively narrow range of materials for which it is suitable, the relatively high spatter levels in CO_2 and potential lack of fusion problems on thicker sections. Spray transfer is suitable for high current downhand welding with most materials but its application on thinner materials is restricted by the high minimum current and its positional capabilities are restricted by the difficulty of controlling a large weld pool. Globular and repelled modes are restricted in application due to arc instability, spatter and relatively high fume levels.

Process physics

The early phenomenological studies of metal transfer have been supplemented by studies of the underlying process physics. The detachment of metal droplets from the filler wire and subsequent transfer to the weld pool have been explained in terms of a static balance of forces [3]. The principal forces involved being:
In free flight transfer of a suspended droplet in the downhand position the detachment forces are opposed by surface tension and vapor jet or plasma forces. At equilibrium (droplet not detached) the forces are balanced:

- gravitational force, F_g
- aerodynamic drag, Fd
- electromagnetic, Fe.
- surface tension, F_st
- vapour jet forces, Fv

In globular transfer at low currents the gravitational force (Fg) is the predominant detachment force whilst vapor or plasma jet forces and surface tension resist transfer. As the current increases the electromagnetic pinch force (Fem) becomes significant and causes constriction of the molten metal neck and a downward droplet detachment component. In short circuiting transfer the predominant detachment forces are surface tension (Fγ) and electromagnetic pinch. This analysis may be extended to give a useful indication of the magnitude of the forces involved and the consequent process behaviour [4] but it does not take into account the dynamic effects which can significantly influence metal transfer.

$$F_g + Fd + F_{en}, = F_{s\,t} + F_v.$$

Control of metal transfer

In order to control metal transfer these forces must be exploited to achieve the desired process characteristics. In conventional GMAW the forces which are developed are a natural consequence of the mean welding parameters but the transient electrical characteristics of the GMAW system may be modified to control process behaviour. The earliest approach to process modification using such techniques was pulsed metal transfer.

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[1] Depending on wire type, diameter and shielding medium.

Pulsed Transfer

Pulsed transfer GMAW was originally developed by Needham et.al. in the 1960's. The concept was to modulate the current between two levels and induce spray type transfer at currents below the normal spray transition threshold. The technique was originally developed using a rotating commutator to switch between the two levels but this was not practical for commercial use. Instead a pulsed power supply which provided pulses of variable amplitude, at multiples of mains frequency was employed. A voltage controlled power source was employed and the pulse was a fixed width and frequency (viz. around 12milliseconds duration at a fixed frequency of 50 or 100 Hz). The pulse amplitude was variable but it was found that this offered a very restricted range of 'optimum' parameters. The development of transistor series regulator power supplies [4] enabled complete control of the current waveform. The early fixed frequency pulsed transfer control was replaced by variable frequency current control capabilities. Optimisation of transfer parameters was guided by the work of Ma [5] working at Cranfield University who established the existence of 'drop spray' transfer. Drop spray occurs in the spray transition range in a very specific current band. When drop spray occurs a spherical droplet typically 20% to 40% larger in diameter than the diameter of the filler wire is formed. The droplet detaches cleanly transfers axially across the arc. The transient melting rate is slightly higher and fume levels are lower in the drop spray range. A ripple free electronic power supply is required to obtain drop spray with a steady DC current but due to the limited current range this type of transfer is difficult to exploit with conventional control techniques. Drop spray may however be artificially induced over a wide current range by using current modulation or pulsed transfer. In fact this effect became the basis for 'one drop per pulse' metal transfer.

In its simplest form the pulse width and amplitude of the pulse are adjusted to detach a single droplet each time the pulse is applied. The relationships between pulse parameters, mean current and wire feed rate can be predetermined for any given consumable combination.

The basic relationships which control variable frequency pulsed transfer are:

This defines the pulse amplitude (I) and pulse duration (t_p) relationship for single drop detachment, the parameter D is referred to as the detachment constant. The relationship may be determined experimentally as shown in figure 2.

$$I^n\ t_p\ = D \qquad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots..(i)$$

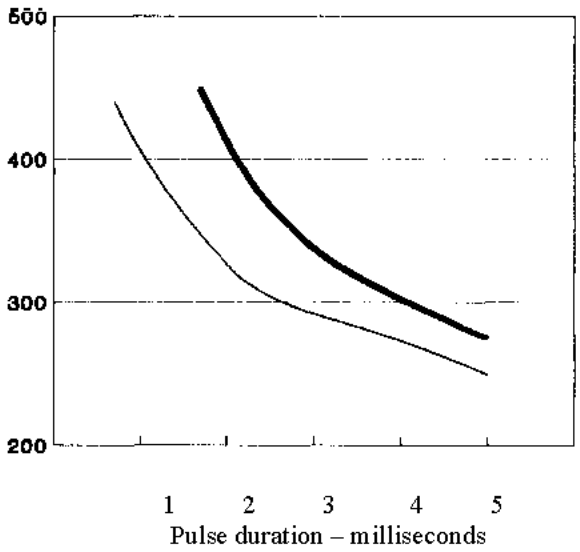

Figure 2. Pulse current-pulse duration relationship for one drop per

pulse transfer (1.2 mm diameter carbon steel wire in argon/5% $C0_2$)

The background current is maintained at a level which is just sufficient to maintain an arc and the background period is varied to adjust mean current. Mean current is given by:
Where I_m is the mean current and I_b and t_b are the background level and duration respectively.

For a given wire diameter, fixed pulse parameters and background current the wire feed rate is proportional to mean current and pulse frequency, ie:

$$WFR = kF = \alpha I + \beta l I^2 \quad \text{..(iii)}$$

Where k, α, and β are constants I is the mean current and l is the electrical stick out or wire extension.

These relationships allow the ideal parameters to be established and automatically adjusted to cover a wide range of mean currents. For example a 1.2mm steel wire will operate satisfactorily over a mean current range from 50 amps up to the spray transition current of around 235 amps with preset pulse parameters (of around 350amps, 3.5 msec). The ability to automatically control wire feed rate and pulse parameters for continuously variable stable operation is known as ‘Synergic’ control [4]. Slight refinements in the control algorithms are often incorporated to take account of the dynamic effects (background preheating and current response rate) of parameters on burn off behaviour but this mode of transfer control offers the following advantages.

- Wide mean current range
- Clean free flight transfer
- Low fume
- Low spatter
- Positional capabilities
- Simple parameter optimization

$$I_m = \frac{I_p t_p + I_b t_b}{t_p + t_b} \quad \text{..(ii)}$$

In the mid 1960’s, attempts were made to apply the pulsed spray transfer method described above to CO_2 shielded the GMAW of steel by [6]. This was attempted in order to overcome the known limitations of using constant voltage/current, which produces “repelled globular transfer”. Using the available technology, a power source was constructed having a selectable pulse frequency of 25 or 50Hz, an adjustable pulse current, independently adjustable background current, and a 150V 15A stabilising supply to avoid the arc extinguishing during long background periods at low current. Tests were carried out using 1.2mm steel electrodes at feed rates from 3.8 to 13.5 m/min (150 to 530 in/min) and corresponding mean currents of 150A to 380A. In the intermediate current range of 200 to 300A, welding could be carried out in the downhand position if the arc was kept very short, so the transferring droplet just touched the weld pool to minimise spatter. At very low mean currents, the weld bead was grossly uneven, due to the low heat input, the fast-freezing nature of the weld pool, and the low frequency and irregularity of metal transfer. At high mean currents, the correspondingly high pulse current produced excessive pool agitation, splashing at the bead edge, and consistent undercutting. The work of Needham and Carter showed that suitable operating conditions could be found for CO_2 pulsed spray transfer, which gave better results than globular transfer using a simple constant voltage (CV) power source operating in the same mean current range. However, better results could be obtained using argon-based gases with less expensive CV power sources. As a result, the pulsed spray CO_2 process was not exploited.

By the mid 1980s, major improvements in power source technology created renewed interest in the pulsed CO_2 process. Japanese researchers [7,8] employed an adjustable square-wave current waveform to optimise behaviour of the process. Using a 1.2mm steel electrode at mean currents of around 250A (8 m/min or 315 in/min wire feed speed) and pulse frequencies of around 38Hz, the metal transfer behaviour was observed using high speed cinematography, and is represented in Figure 3. The transfer of the large droplet occurs approximately mid way through the pulse period. The replacement droplet is developed during the remainder of the pulse period, and during the background period. The distortion of the transferred droplet at the high current is clearly visible in the photographic frames of Figure 4. As discussed previously, the constricted CO_2 arc at high currents produces large upward asymmetrical forces on the droplet at the same time that electromagnetic pinch forces create necking of the droplet.

In contrast to CO_2 pulsed transfer, pulsed transfer in argon occurs at the end of a relatively short pulse period (1.5 to 5 ms typically [4]), and the droplet is propelled directionally to the weld pool during the background period under low current. The CO_2 transfer exhibits a much high spatter rate, and this characteristic is unavoidable due to the operation of the transfer. Similar behaviour has been reported by other researchers employing similar techniques [9].

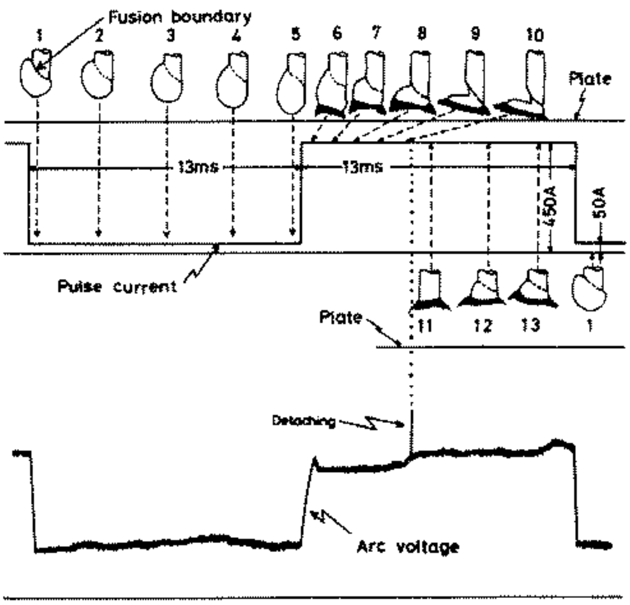

Figure 3 Example of droplet behaviour and waveforms in pulsed CO_2 [Matsuda et. al., 1985]

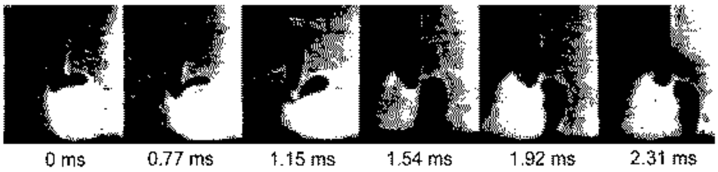

Figure 4 High speed cinematography of droplet transfer [Matsuda et.al. 1985]

Due to the inherent mechanism of the CO_2 process, improvements in pulsed transfer behaviour over those described in these papers has not been demonstrated over the past decade. Further advances in power source technology and process modelling have not, as yet, generated a solution to the problems.

Controlled dip transfer

The short circuiting or dip transfer mode was a exploited in the 60's with CO_2 as the principal shielding medium. It was excellent for thin sheet steel and prior to the introduction of pulsed transfer it was the only way that GMAW could be employed for positional welding of thicker sections of steel. Unfortunately the process generated spatter and arc stability was poor unless the parameters were very carefully adjusted. The process could be optimized by careful control of the current waveform using a secondary DC inductance [10][11]. A costly variable inductance and some expertise in its adjustment were however necessary and the process was still susceptible to instability and random spatter events. The reasons for this unstable operation in CO_2 has been explored by Cuiuri [12]. Although these problems could be overcome to some extent by using argon/ CO_2 gas mixtures the cost and availability of CO_2 justified further research.

Unlike the open arc process, it has been shown that the CO_2 shielded short-circuiting process can be greatly improved by electronic control techniques. In the early 1970s, research by Boughton and MacGregor [13] demonstrated techniques for reducing weld pool disturbances and spatter. This involved reduction of current for 0.5 to 1.5ms after the start of the short-circuiting period, allowing the droplet formed at the tip of the electrode to "wet in" to the weld pool, This minimises repulsion forces which would cause the short to blow apart and generate spatter. After the wetting-in time is complete, the current is increased to promote normal metal transfer to the weld pool. The second step involved the reduction of the current in the short-circuit, just prior to the rupture of the neck connecting the electrode to the weld pool. This step avoids generation of spatter and pool disturbance when the neck ruptures. Although the equipment functioned well in a laboratory using a mechanised welding rig, it was not possible to accurately predict the point of short-circuit rupture as conditions changed; particularly contact tip to workpiece distance (CTWD). In the mid 1980s, Ogasawara et al [14] devised a reliable means of predicting the short-circuit rupture. Improvements to the arcing period waveform were also devised, namely, applying a current pulse of suitable magnitude and duration to produce an adequate arc length to avoid premature short-circuiting. In 1989, Stava [15] reported another commercially available power source which further improved the prediction of the short-circuit rupture, and also incorporated circuitry designed specifically to turn off the welding current very rapidly (within 50 microseconds) when such an event is predicted. An alternative approach to generating similar current waveforms for the short-circuiting CO_2 process has recently been described by Ou et al [16]. This approach uses programmable voltage-current characteristics rather than time-oriented wave shapes. This results in a power source that is more self-adaptive to the process, and is more conducive to the implementation of a "one knob control" facility. A further development of this type has been reported by Cuiuri [17]. In this case an optimum droplet size is achieved during the arcing period and the peak current level is clamped at a low level during the short circuit. This approach avoids the demanding requirements of high current switching prior to the end of the short circuit.

The developments described above have concentrated on manipulating the power source output current to achieve the desired process behaviour, while feeding the electrode at a constant rate. Researchers have also used mechanical means of rapidly adjusting the wire feed rate to improve the process, without resorting to complex power sources. Earlier attempts involved the unidirectional stepped feeding of wire [18,19,20]. This approach used the stepped feeding to dictate the dipping frequency of the process. More recently, Huismann [21] has described in detail the operation of a dynamic wire feeding system which rapidly reverses the direction of the electrode at the start of the short circuit. In this system, the dipping frequency is not enforced. Instead, the wire feeding control system merely responds to the incidence of a short circuiting event. The withdrawal of the electrode away from the weld pool guarantees that the rupture of the short circuit can successfully occur even at low currents for large electrodes, with minimal disturbance to the weld pool. Once the arc is re-established after the short circuit, the wire is fed forward at the desired feed rate. Although tests were conducted at relatively low wire feed rate and current (150A) with a 1.6mm steel electrode in Ar-3%O_2. The dynamic reversing is a significant departure from prior art, and there is no apparent barrier to its use with the CO_2 process. The current control techniques described above significantly improve dip transfer performance in CO_2 but they are restricted to a low mean current range and travel speed. (Typical operating conditions for a butt weld using 0.9mm wire are; mean current 120 amps, travel speed 400mm/min). Increasing the mean current into the globular range is ineffective for the reasons discussed above. In argon based gases this restriction has been removed by employing a longer electrode stick out (in the so-called Rapidarc™ process [22] with a conventional CV power supply to increase the operating range.

The present authors have produced similar results in CO_2 by employing transient current control. The experimental power source used [23] is shown in figure 5. It incorporates all the circuit features required for optimised control of the short-circuiting GMAW process . It has a peak current output capacity of 600A, and a current turnoff capability of 20,000 A/ms. Using this equipment a range of experiments have been carried out using 0.9mm and 1.2mm diameter steel electrodes.

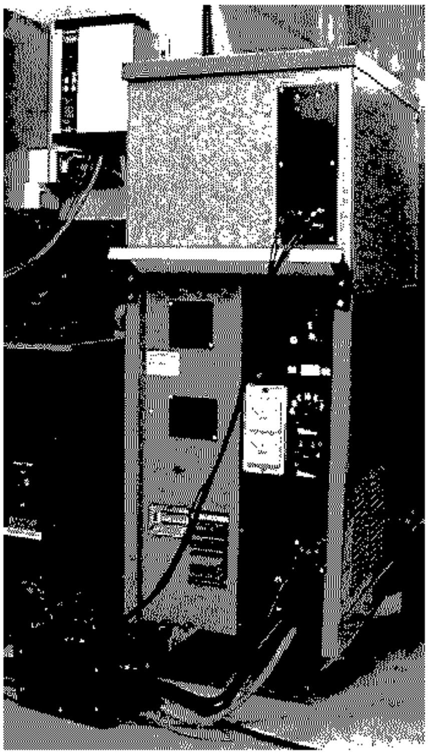

Figure 5 Experimental power source

The welding parameters were progressively adjusted to produce the highest deposition rate at certain CTWD values, while maintaining low spatter, high stability and good bead appearance. The results are summarised as follows:

Table 1 Summary of maximum deposition rates

Wire type AWS A5.18	CTWD mm	Wire feed rate m/min [in/min]	Dep. rate kg/hr	Current Amperes
0.9mm ER70S-6	12	17.5	5.2	250
0.9mm ER70S-6	35	21.0	6.3	180
1.2mm ER70S-4	16	10.0	5.3	290
1.2mm ER70S-4	35	13.5	7.1	245

Welding travel speeds varied between 400 and 1200 mm/min for these tests. It should be noted that the welds performed at these deposition rates are achieved using conditions which were consistently repeatable, and not at the edge of the performance envelope. For example, the 1.2mm ER70S-4 electrode at a CTWD of 35mm has been operated at 15.0 m/min. However, at this deposition rate the spatter level was considered unacceptably high (visual assessment), although the bead quality had not significantly deteriorated in comparison to that at 13.5 m/min. The deposition rates achieved with 1.2mm electrodes using short-circuiting transfer are comparable to those described in the literature using pulsed spray transfer. The major advantage of short-circuiting transfer is reduced spatter and improved arc stability, with a consequent improvement in “operator appeal”. The stability index for each weld was evaluated using the relationship:

$$Stability\ Index = 1 - \frac{Std\ Deviation\ of\ weld\ cycle\ duration}{Mean\ Value\ of\ weld\ cycle\ duration}$$

All welds which were deemed to be suitable had stability indices greater than 0.80. Most welds achieved a stability index between 0.85 and 0.90. Exceptionally stable welds achieve indices up to 0.94. Although the deposition rates of 0.9mm electrodes in CO_2 is not discussed in the literature, short-circuiting transfer using conventional equipment can be performed up to approximately 9 m/min to obtain reasonable weld quality. Above this, increasing spatter and poor stability rapidly degrade the process. The results in the above table indicate a doubling of the deposition rate, while maintaining process quality. The short circuit frequency of most welds lies in the range of 35 to 50Hz. These dipping frequencies are lower than those achieved by conventional short-circuiting processes.

Extended transfer modes

The techniques described above extend the capabilities and improve the control of the GMAW process but attempts to enhance the deposition rate have also been reported. The high deposition variants of GMAW rely on DCEN operation, high operating current, extended electrical stick out or a combination of these effects. Operating GMAW with electrode negative has been known since 1955 [24] to increase the burn off rate of the wire by up to 50% in the spray transfer mode [25]. The problem is that steel wires behave somewhat erratically when DCEN is used. To overcome this Lesnewich used surface activants whilst Norrish used an argon based gas mixture. Although the technique has not been use commercially with solid wires it has been adopted for high deposition welding with metal cored wires.

The relationship between melting rate and current has been quoted above (equation iii) if this is further examined:

$$V = \alpha I + (\beta l I^2)/a$$

It can be seen that the first term represents arc heating whilst the second term represents the resistive heating in the wire extension.(a is the cross sectional area of the filler wire)

Increasing ‘I’ or ‘l’ or decreasing ‘a’ will cause the burn off rate to increase. In the 1970’researchers at Union Carbide in the USA demonstrated a 30% increase in deposition rate with a 1.2mm wire, and a 35mm extension at around 350 amps in an argon based mixture. Halmoy [26] also indicates that with the same wire diameter at 350 amps the deposition rate would be expected to increase from around 120 to 180 g/min when the electrical extension is increased from 25 to 35mm. If the current is increased further the burn off rate increases (in proportion to the square of the current), the electrode extension becomes molten and rotating spray occurs. This technique has also been commercialized under the trade name T.I.M.E.™ and Rapidmelt™. Although the process operates satisfactorily under an argon based gas shield Helium is often added to the gas mixture to promote fusion of the parent material.

The most recent development in high productivity GMAW has been the use of multi-wire systems. These commonly involve two wires sharing a common gas shield or two adjacent torches. The two wires may be operated from a single power source or independent power supplies. Blackman [27] has attempted to classify the operating modes and demonstrate the advantages of the process. Deposition rates of up to 24kg/hr are claimed and the process is resistant to undercut.

Summary

The metal transfer mechanisms initially observed in the 1960's have been extended by research into improved process control and attempts to increase deposition rates. The International Institute of Welding (IIW) proposed a classification in 1990 and a version of this classification, modified to take account of the developments reported above is reproduced in table 2 below. The table indicates the way in which the operanting range of the GMAW process has been extended by process and equipment modification. Research into metal transfer control is continuing in an attempt to further increase operating flexibility and reduce fume.

Table 2. Modified IIW metal transfer classification.

Transfer Group	**Sub Group**	**Example**	**Commercial name**
1.1 Globular	1.1.1 Globular Drop Transfer	Low current GMAW aluminium	
	1.1.2 Globular repelled	CO_2 shielded GMAW	
1.2 Spray	1.2.1 Projected spray	GMAW above transition current	
	1.2.2 Streaming spray	High current GMAW	
	1.2.3 Rotating spray	High current extended stick out	T.I.M.E™ Rapidmelt™
	1.2.3 Explosive transfer	GMAW – poor quality steel wires	
	1.2.4 Drop spray	GMAW at transition current and pulsed transfer	
	1.2.5 Multiwire	Multiwire GMAW	
2.0 Bridging	2.1 Short circuiting	Conventional dip transfer GMAW	
	2.2 Bridging without interruption	Filler wire addition inGTAW	
	2.3 Current controlled dip transfer	GMAW steel with current controlled power source	STT™ , Optarc™
	2.4 Controlled wire feed short circuit mode	GMAW with wire feed oscillation	CSC
	2.5 Extended stick out GMAW	High deposition short circuit transfer GMAW	Rapidarc™, Synchrowire
3.0 Slag protected transfer	3.1 Flux wall guided	SAW	
	3.2 Other modes	MMAW, FCAW	

Modifications to IIW classification: ☐

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