Arc-Voltage and -Current Transients During Metal Transfer

By G. L. DATTA*

Introduction

The not-so-simple mechanisms of metal transfer constitute a major area of interest to researchers in the field of physics of arc welding. A thorough understanding of the mechanisms involving the metal transfer can help the welding engineers to a large extent in controlling the physico-metallurgical characteristics of the weldment and in designing suitable welding power sources. A great deal of research has already been conducted on the theory of metal transfer in arc welding and the available literature is quite extensive[1]. However, the continuing research activities throughout the world is only a pointer to the very complicated nature of the problem requiring a large number of parameters to be controlled.

The metal transfer is ordinarily known to take place in three modes[2], namely—short-circuit, free-flight and spray transfer. In short-circuit transfer, the molten droplet momentarily bridges the arc to form a short-circuit and subsequently the bridge is broken with the detachment of the molten droplet from the electrode. In free-flight transfer, the droplet gets detached from the electrode (without causing any short-circuit) and traverses through the arc to reach the molten pool at the crater. The short-circuit and free-flight together constitute a globular mode of metal transfer. In spray transfer which is associated with high current densities and hence not common to coated electrode process, the molten droplet splits up into minute fractions due to some sort of explosion occurring within the droplet.

Most of the research in this field has been confined to metal-arc inert-gas shielded (MIG) welding process, though arc welding with coated electrodes seems to be the major welding work undertaken. Moreover, majority of the researchers adopted high speed cine photography[3–9] (speed ranging from about 3000 to 14000 exposures per second) which is rather expensive and involves a time consuming procedure for subsequent evaluation. Simple conventional pen-recording and oscillography[10–11] have been used by a few researchers for a limited purpose. It appears that these conventional methods can be conveniently adopted to great advantage to unfold newer aspects of the metal transfer.

In the present investigation, the behaviour of arc-voltage and current transients in arc welding with coated electrodes has been studied and the mechanism of the formation and transfer of the molten droplet has been discussed.

Experimental Technique

The records and oscillographs of arc-voltage and current transients were obtained by using a high speed pen-recorder and an oscilloscope with photographic arrangement, the speeds chosen being 12.5 cm/sec

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in both the cases. Beads were deposited on mild steel work pieces with the help of a pre-set feed machine using light coated 10 SWG electrodes.

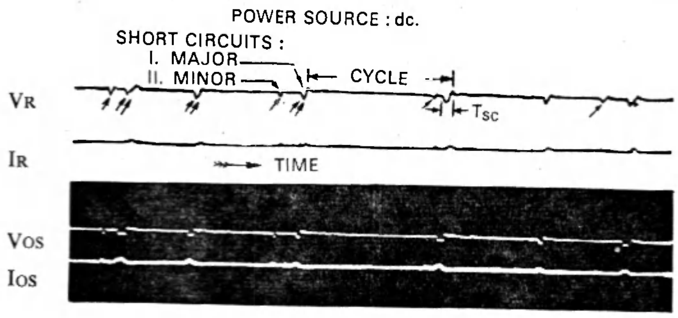

Fig. 1. Photograph of records & Oscillographs (synchronised) of arc voltage (V) & current (I) ; suffix 'R' refers to the former and 'OS' to the latter.

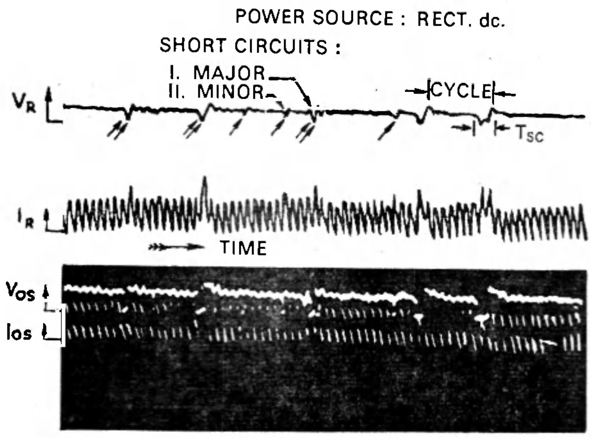

Fig. 2. Photograph of records & Oscillographs (synchronised) of arc voltage (V) and current (I) ; suffix 'R' refers to the former and 'OS' to the latter.

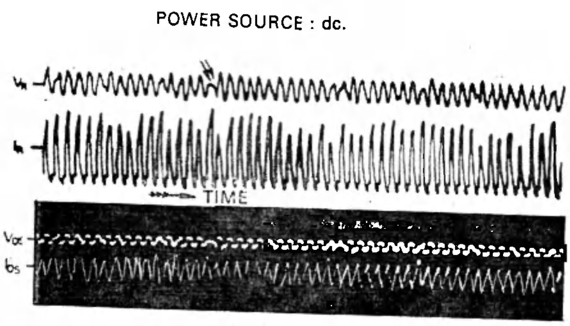

Fig. 3. Photograph of records & Oscillographs (synchronised) of arc voltage (V) and current (I) ; the suffixes 'R' & 'OS' refer to pen-recorder & Oscilloscope respectively.

Experimental Results

Typical records and oscillographs (speed synchronised) of arc-voltage and -current transients are shown in Figs. 1 to 3. The figures show that there are fluctuations from the mean levels of arc-voltage or current and that these fluctuations could, broadly, be classified as 'minor' and 'major'. In these fluctuations, the voltage falls and the current rises by a substantial amount from their respective mean levels. Comparing the records and oscillographs, it is further seen that the minor fluctuations are of lesser durations than the major ones. The records show that the fall of the voltage (or the rise of the current) is of different magnitudes for minor and major fluctuations. But the oscillographs indicate that the magnitude is same irrespective of the type of fluctuation. Since the minor fluctuation is of small duration, the recorder possibly could not indicate the actual level of change due to its inertia.

Apart from these fluctuations, there are other fluctuations inherent to the nature of the power source (e.g., 50 cycles per second for ac or 100 cycles per second for rectified dc).

The minor fluctuations are observed to occur in between two major fluctuations. From one major fluctuation to the immediately next major fluctuation, there exists a phenomenon repetitive in nature which has been referred to as a 'cycle'. In each figure a typical cycle has been marked. An analysis of a cycle reveals that the period of a cycle can be said to consist of the following sub-divisions :

(i) *Non-Uniform Rate of Fall of Voltage*

Referring to Fig. 4, the mean arc-voltage is found to fall from a to b in a period T_1, the rate of fall being rather fast and non-uniform.

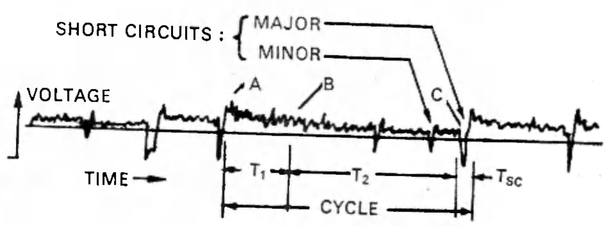

Fig. 4. Typical Arc Voltage Transient.

(ii) *Gradual and Slow Rate of Fall of Voltage*

From b to c, the voltage falls uniformly and gradually by a certain amount in the period T_2. The period T_2 is comparatively more than the period T_1 and the amount of fall in the period T_2 is less than that of the period T_1.

(iii) *Instantaneous Fall of Voltage to Zero.*

At the end of the period T_2, the arc-voltage is seen to fall instantaneously to almost zero. This instantaneous fall is, however, not present in all the cases, as can be seen from Fig. 5. Whenever the voltage falls instantaneously to zero, it maintains at that level for a certain duration T_{sc}, called 'short-circuit' period (since only a short-circuit of the arc can make the arc-voltage zero). At the end of the period T_{sc}, if present, the voltage rises again instantaneously to a value existing at the start of the cycle.

An analysis of a current transient depicts that whenever the voltage is falling the current is increasing (becuse of the drooping V-I characteristics of the power source).

Fig. 5. Oscillograph of a typical Arc Voltage transient in free flight mode of metal transfer.

From the foregoing analysis of a cycle, it can be clearly seen that a cycle is related to the growth and detachment of a molten droplet from the electrode. Initially in the period T_1, the fall of voltage is rather fast indicating that the rate of growth of the molten droplet is fast at the initial stage of its formation. The period T_1 is about 1/5th of a cycle and within this time the rate of growth seems to stabilize attaining a uniform rate of growth as indicated by the gradual fall of the voltage in period T_2. The slope of the curve in this period is an indication of the rate of growth of the molten droplet. This finding of the existence of the slope contradicts Orton and Needham's (1949)[10] observation but corroborates Sunnen's (1962)[8] conclusions.

The total fall of voltage in the periods (T_1+T_2) is an indication of the size of the molten droplet formed. At the end of the period T_2, if the arc-length is sufficiently low, a short-circuit is formed between the molten droplet and the molten metal at the crater, and the droplet subsequently gets detached from the electrode giving what is known as a short-circuit mode of metal transfer. This type of metal transfer is indicated by the instantaneous fall of the voltage to zero. Otherwise when the arc-length is sufficiently large, the molten droplet gets detached without causing any short-circuit, giving a free-flight mode of metal transfer.

When a short-circuit takes place, the voltage becomes zero and the current shoots up to a high value (depending on the current setting). The period T_{sc} indicates the duration for which the short-circuit continues which is followed by the detachment of the molten droplet and restriking of the arc. If the transfer takes place without short-circuit, the period T_{sc} is absent in the cycle and at the end of the detachment of the molten droplet a new cycle starts.

In the case of a short-circuit mode of metal transfer, a cycle ends with a major short-circuit (or fluctuation). Thus it is concluded that each major short-circuit leads to metal transfer. Where as, a minor short-circuit occurs in between a cycle and hence such short-circuits do not lead to any metal transfer (or of negligible amount). It is believed that the molten droplet oscillates due to various causes (like gas evolution, plasma flow etc.) and momentarily causes short-circuits of the arc. But possibly because of the contact area being too small or contact having formed by the slag coating on the surface of the molten droplet, such contacts get broken explosively within a very short duration of its formation. The breaking up of the contact is due to high current (associated with any short-circuit) passing through the small or poor contact area. This so-called minor short-circuits appear as dots in the oscillographs.

Fig. 1 shows a short-circuit mode of metal transfer using a dc power source. Single and double arrows indicate the minor and major fluctuations respectively. Each such fluctuation, whether minor or major, is really a short-circuit. The oscillographs clearly show that the short-circuits are formed instantaneously and at the end of the period T_{sc}, the rise of voltage to its, pre-T_1 period level is also instantaneous. This is however, not seen from the records presumably due to its inertia. The figure further shows that each cycle is not of the same duration, indicating the unsteadiness of the system.

Figs. 2 and 3 also show a short-circuit mode of metal transfer using rectified dc and ac power sources. Fig. 2 indicates that the voltage trace almost behaves like that of a dc power source (further reference to Fig. 6) excepting very fine variations about the mean, whereas the current transient retains its inherent variations. This is because of the inherent rectification of the arc-voltage which is a sum total of cathode-anode drops plus column drop and which remains constant

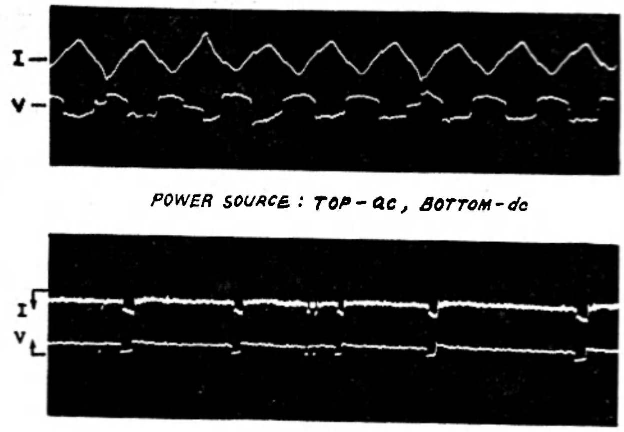

Fig. 6. Oscillographs of Arc Voltage and current transients. Note the transformed Voltage pattern (Top Source—ac).

under a given set of conditions (like arc-length, current, arc atmosphere etc.) irrespective of the inherent variations of the power source except at its zero level. At the zero level of the source voltage, the arc would tend to get extinguished making arc-voltage also to fall to zero. The current transient does not undergo such rectification. The voltage transient in the case of the ac source (Fig. 3) transforms into a square wave form.

From these figures, it can be stated that the records show similar features of variations as the oscillographs. The mode of metal transfer whether short-circuit or free-flight and the durations of cycles can as well be ascertained from records alone, which are much easier and quicker to obtain. But for studying the short-circuit durations, oscillographs are necessary. It is also seen from this investigation that the voltage and the current transients can be mutually exclusive and hence one of them can as well provide all the informations regarding the behaviour of a molten droplet.

Summarizing the foregoing discussion it can be stated that the arc-voltage transient has been established to be related to the formation of the molten droplet. The rate of formation of the molten droplet is a function of the rate of heat transfer from the arc. It has been accepted by researchers[9,12] that the arc emanates from an 'active surface' situated near the tip of the droplet. In order that the melting can proceed, heat generated at the active surface must transmit through the droplet to reach the solid surface on the electrode. If the droplet is large, the heat transfer is naturally slower than when minute amount of molten metal is left over at the electrode as at the instant of the start of a cycle. With the formation of the molten droplet, the rate of heat transfer decreases which in turn may give rise to slower rate of melting. Thus the melting rate does not seem to be constant throughout the duration of the formation of the droplet. During the short-circuit period there is no melting (or of negligible amount) and since the electrode is being fed continuously, this amounts to a decrease in the distance between the surface standing for the melting zone on the electrode and the surface of the molten pool at the crater. After the detachment of the molten droplet, the arc restrikes, the arc being nearer to the melting zone the heat transfer is more efficient and the melting appears to be faster during the period T_1 accounting for the reduction in the distance between the melting zone (surface) and the molten pool at the crater which occurred during the previous short-circuit. The melting rate subsequently equalizes the electrode feed rate in the period T_2. Thus, on the average the electrode melting and its feed balance together.

Conclusions

(i) The arc-voltage transient indicates the different stages of the formation of the molten droplet and the manner of its subsequent detachment.

(ii) The rate of growth of the droplet is faster during the early stage of its formation and subsequently the rate decreases but attains a steady value.

(iii) In short-circuit mode of metal transfer, two types of short-circuits occur—major and minor, only the former standing for metal transfer.

(iv) In the case of an ac power supply, the arc voltage assumes a square wave form while the current maintains its (source) alternating nature (i.e. cine wave form).

Acknowledgement

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