Study on the Mechanism of Spatter Produced by Basic Welding Electrodes

The explosion of CO gas bubbles appears to be a major cause of spatter

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ABSTRACT. In this work a device was made to control the current at three stages of short circuiting welding: at the beginning of short circuiting, during the overall period of short circuiting, including the breaking stage, and at the arc reinitiating stage. By investigating the effects of these currents on the spatter produced by basic welding electrodes, the decisive parameter which determined spatter quantities was identified as the current at the short circuit breaking stage. On the basis of the experimental results from the combined effect of short circuiting current and the oxygen potential in the covering, it was found that the major process causing spatter was the explosion of CO gas bubbles, which resulted in the breakage of the short circuiting bridge. The high density of current intensified this explosion and increased the spatter quantity. The spatter mechanism caused by the explosion of gases was identified by studying the metal transfer using laser back-light, high-speed photography and x-ray, high-speed photography to record two images simultaneously, along with arc sound and arc voltage oscillographs.

Introduction

The quantity of spatter produced during welding is one of the major parameters in the evaluation of the operating characteristics of basic electrodes. A great amount of work has been done to investigate the mechanism of spatter production. The phenomena and various mechanisms of spatter have been summarized in an excellent book (Ref. 1). It is well known that the metal transfer from a basic electrode takes the mode of short circuiting. Research work has focused on the spatter mechanism produced in the short-circuiting process. The viewpoints obtained can be summarized as follows:

1) Electric Explosion (Ref. 2): Under the action of the magnetic force produced by a high, short circuit current, the metal bridge shrinks in cross section and the density of the short circuit current increases further. The metal bridge overheats and evaporates, resulting in an explosion. The current surge rate, dI/dt, is the most important factor affecting spatter production.

2) Gas Explosion (Ref. 1): The surplus oxygen and the carbon contained in the melted metal react intensively with each other in the high-temperature zone, which results in violent evolution or explosion of CO gas.

3) Gas Impact (Ref. 3): The atmospheric gas is heated and expanded by abrupt arc reinitiation after short circuiting. The melted metals in the weld pool and remaining drop are blown off through impact.

4) Spatter Caused by Instantaneous Short Circuiting (Ref. 1): Instantaneous short circuiting means a short circuiting of a very short duration without metal transfer. During the breaking of the metal bridge, which is very thin, a small quantity of spatter may be produced.

In order to effectively control the spatter in welding, it is necessary to identify what the mechanism is. This work involved investigation and analysis of the effect of current densities at various stages of short circuiting on the quantities of spatter. The effect of gas explosions was analyzed. The mechanism and the controlling factors of spatter were thus identified.

KEY WORDS

Spattering
Welding
Basic Electrodes
Short Circuiting
High-Speed Photograph
CO Gas Explosion
SMAW
Oscillographs

Experimental Procedure

Materials

Commercial basic electrodes were used and two series of experimental electrodes were prepared. The first series of electrodes was designed to alternate the oxygen potential and used three types of core wires with various alloying levels. Their compositions are shown in Table 1. The oxygen potential in the electrode coverings was changed by varying the ratio of oxidant (marble) and deoxidant (Fe-Si and Fe-Mn) contents. The oxygen potential was defined in Ref. 5 by the following formula:

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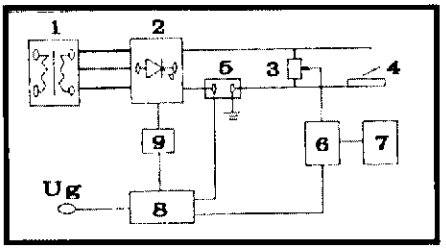

Fig. 1 — Block diagram of device for setting currents at various stages of a short circuit. 1 — Transformer; 2 — thyristor rectifier; 3 — adjustable resistor; 4 — welding arc; 5 — shunt; 6 — feedback circuit; 7 — single plate microprocessor.

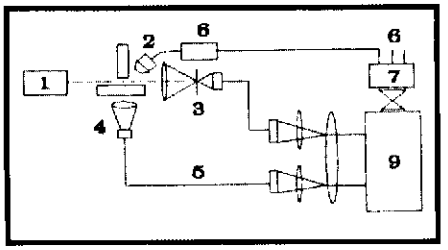

Fig. 2 — Schematic illustration of apparatus for laser back-light high-speed photography that records two images simultaneously with arc sound and voltage oscillographs. 1 — laser back light; 2 — microphone; 3 — aperture; 4 — lens; 5 — optical fiber; 6 — magnifier with band filter; 7 — light oscillograph; 8 — arc voltage signal; 9 — high-speed camera.

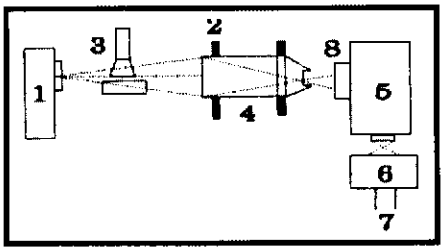

Fig. 3 — Schematic illustration of apparatus for x-ray back-light high-speed photography. 1 — X-ray tube; 2 — lead shelter; 3 — electrode; 4 — image magnifier; 5 — high-speed camera; 6 — light oscillograph; 7 — arc voltage and sound signals; 8 — lens.

$$Eo = Cc/100 - \Sigma (Cm \times Mc \times Y)/(Wa \times X)$$

where: Eo represents quantity in moles of the remaining CO_2, calculated by subtracting quantity of CO_2 that could be deoxidized by alloying elements from that of the total CO_2 evolved from marble in 100-g covering; Cc is marble wt-%; 100 is molecular weight of marble ($CaCO_3$); Cm is the wt-% of a deoxidizer; Mc is the wt-% of alloying element in the deoxidizer; Wa is the atomic weight of the alloying element; X, Y are the ratio of the numbers of atoms in the oxide M_XO_Y.

The second series of electrodes contained up to 3.5% of three types of rare earth metal additives, *i.e.*, lanthanum oxide, a mixed oxide of rare earth metals, and an alloy of heavy rare earth metal. The compositions of the covering are shown in Table 3. The compositions of the test pieces are shown in Table 4.

Device

Figure 1 shows the block diagram of a device made for setting currents at various stages of a short circuiting process. At the beginning and the ending of a short circuit, the arc voltage drops down and then rises up abruptly. A single plate microprocessor accepts these signals and controls a trigger circuit of a thyristor rectifier welding machine. The currents at 1) the beginning of a short circuit, 2) during the overall period of short circuiting, including its breaking stage and 3) at the reinitiating stage, could be set.

A device was made to record and statistically analyze the parameters of the short circuiting process. Histogram of event numbers against the duration of the short circuits could thus be obtained. Short circuits with a duration of less than 2 ms were referred to as instantaneous short circuits.

An apparatus for laser backlight, high-speed photography was used (Ref. 4). Using this apparatus, high-speed pictures (1000–2000f/s) with simultaneous recording of a metal transfer image, arc side image, arc sound oscillograph, and arc voltage oscillograph could be obtained. Figure 2 shows a schematic illustration of the apparatus.

An apparatus for x-ray, back-light, high-speed photography was used to observe gas bubbles forming and evolving in drops of melted metal or weld pools. Figure 3 shows its schematic illustration. Detailed information on the high-speed photography can be obtained from Ref. 4.

Spatter Collection

All welding was carried out on plates (100 x 300 x 10 mm) put in an open box (400 x 500 x 200 mm) using 170 A direct current electrode positive (DCEP) welding current and an arc voltage of 23–24 V in a flat position. All of the spatter deposited on the plate and in the box was collected. The slag on the surface was detached by grinding and metal drops were collected by a magnet. The coefficient of spatter was defined as the ratio of the weight of spatter to that of the consumed core wire of electrodes.

Results of Experiments

1) Effect of the current at the beginning stage of a short circuit upon the quantity of spatter

The welding condition was set with a welding current of 170 A, arc voltage of 23–24 V and short circuiting current of 250 A, using commercial basic electrodes. Peak current at the beginning stage (within 4.5 ms) was set at 50, 100, 150, 200, 250, 300, 350, and 400 A, respectively. The oscillographs of the current and the voltage are schematically shown on Fig. 4. The spatter coefficients are plotted against the peak currents at the beginning stage of the short circuiting process in Fig. 5. In the same diagram the curves drawn indicate the event numbers of the short circuits with a duration of 2–5 ms and that less than 2 ms (instantaneous).

2) Effect of current at the arc re-initiating stage after short circuiting on the quantity of spatter

At the arc reinitiating stage, the gas in the atmosphere around it is heated and expands abruptly. It is believed that the expanding gas has a strong impact on the weld pool, which results in spatter. To determine if this idea was valid, the currents at the arc reinitiating stage were set to 50, 100, 200, 300, and 400 A. The arc currents and voltage oscillographs were schematically shown in Fig. 6. The spatter coefficients are plotted against the cur-

Table 1 — Compositions of Core Wires (wt-%)

Type	C	Mn	Si	S	P
H08A	0.06	0.45	0.01	0.03	0.03
H08MnA	0.07	1.05	0.06	0.03	0.03
H08Mn$_2$Si	0.07	2.05	0.76	0.03	0.03

Diameter 4.0 mm.

Table 2 — Compositions of Electrode Coverings with Various Oxygen Potential (wt-%)

Fluor-spar	Titanium dioxide	Sodium carbonate	Fe-Ti	Powder of Fe	Marble	Fe-Mn	Fe-Si	Eo
35	3	2	3	13	40	0	0	0.37
35	3	2	3	13	35	3.5	1.5	0.22
35	3	2	3	13	30	7.0	3.0	0.07
35	3	2	3	13	25	10.5	4.5	−0.08
35	3	2	3	13	20	14.0	6.0	−0.23
35	3	2	3	13	15	17.5	7.5	−0.37

Fe-Ti with 38%Ti, Fe-Mn with 78%Mn, Fe-Si with 48%Si.
Bonding agent is 27% water glass, diameter 6.4 mm.

Table 3 — Compositions of Electrode Covering Containing Rare Earth Metal Alloys or Oxides (wt-%)

Marble	Fluor-Spar	Titanium Dioxide	Sodium Carbonate	Fe-Ti	Fe-Si	Fe-Mn	Ca-Si	Fe-Powder plus rare earth agents	Eo
35	35	3	1	6	2	6.5	1.5	8.75	−0.065 to 0.032

27% water glass as bonding agent, Ca-Si with 31%Ca.

rents set at arc reinitiation — Fig. 7. The curve indicating the total number of short circuits is drawn in the same diagram.

3) Effect of current at the short circuit breaking stage on the quantity of spatter

It is well recognized that the current at the short circuit breaking stage (the value corresponding to the moment just prior to the abrupt rising of arc voltage in Figs. 4, 6, and 8) has a highly significant effect on spatter production. However, since it is very difficult to detect the signal predicting a short circuit breakage, the attempt to set a current just prior to a short circuit breakage was unsuccessful. In this work, the current during the overall short circuiting process, including its breaking stage, was set at 50, 100, 150, 200, 250, 300, 350, and 400 A, respectively. The current at arc reinitiation was fixed at 170 A. The oscillographs of current and voltage are schematically shown in Fig. 8. The effect of the current at the short circuit breaking stage on the spatter quantity could be evaluated by looking at the difference between the spatter quantities caused by the current during the overall short circuiting process and that caused by the current at the beginning and reinitiating stages. The spatter coefficients are plotted against the current set for the total duration of short circuiting in Fig. 9. Corresponding coefficients of spatter caused by the current at the beginning stage of short circuiting and at arc reinitiation are plotted in the same graph. The effect of the current at short circuit breakage is shown by the curve calculated by using the former and the two latter curves described above.

4) Effect of oxygen potential on the spatter quantity

For electrodes whose covering compositions are shown in Table 2, the oxygen potential was adjusted by alternating the ratio of the content of oxidant marble to that of the deoxidants Fe-Mn and Fe-Si in the covering and by changing the core wire using various deoxidant elements Mn and Si (Table 1). The welding condition with these electrodes was: a welding current of 170 A, an arc voltage of 23–24 V and a short circuiting current of 250 A. The spatter coefficients measured are plotted against various contents of marble and deoxidants in Fig. 10. It indicates that spatter coefficients decrease apparently with decreasing oxygen potential in the coverings. The contents of deoxidant elements in the cored wires have the effect of depressing the spatter quantities in the higher oxygen potential zone. However, it is impossible to use the deoxidant only in the core wire to diminish the spatter. The declining effect of deoxidant elements in the core wire in the low-oxygen potential zone shows that the practical approach of decreasing the spatter is altering the deoxidant in the covering.

5) Combining effect of oxygen potential and short circuiting current on the spatter quantity

Using electrodes with ratios of marble to deoxidants content of 40:0 and 15:25 in the covering, welding with various short circuiting currents was carried out at constant currents for welding and arc reinitiating. The spatter coefficients measured during welding with various short circuiting currents are plotted in Fig. 11.

In order to investigate the effect of rare earth metal additives on spatter quantities, welding was carried out using electrodes with various rare earth metal alloys and oxides in the coverings under normal welding conditions. The spatter coefficients are plotted against the rare earth metal alloy and oxide contents in Fig. 12. X-ray, back-light, high-speed photography was used to observe the drop transfer from electrodes and to measure the diameters, d, of shrinking metal bridges, just prior to short circuit breakage. The results are shown in the same diagram. From Fig. 12 it is found that rare earth metal oxides increase the spatter production, however, rare earth alloys decrease it. It is very interesting that the trends of spatter variation coincide with the variations in metal bridge diameters just prior to the short circuit breakage.

6) Observation of spatter and gas bubbles in melted metal by high-speed photography

Figure 13 shows three typical processes of short circuit breakage, taken by laser back-light high-speed photography. The metal bridges exploded during breaking, indicated by jumping of the arc voltage, violent vibration of arc sound curves and the reappearance of the arc spot. These phenomena are shown by the thick lines, thin lines and light spot im-

Table 4 — Compositions of Test Pieces (wt-%)

C	Si	Mn	O
0.19	0.14	0.46	0.0027

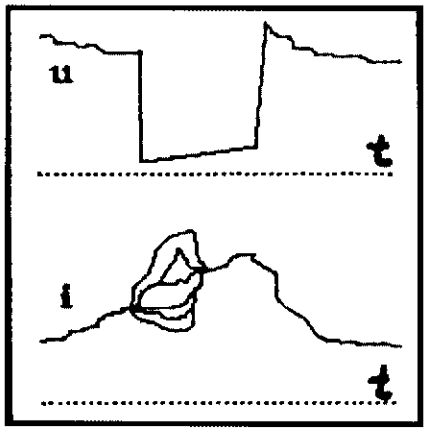

Fig. 4 — Schematic oscillographs of voltage and current at the beginning stage of the short circuiting process.

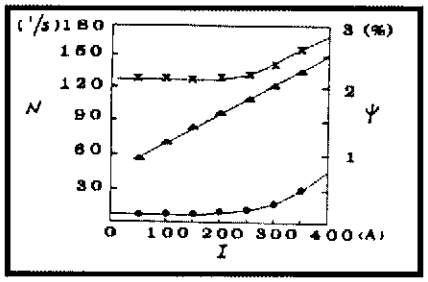

Fig. 5 — Effect of the current at the beginning stage of short circuiting process upon the spatter coefficient "x" and the event numbers of short circuiting with a duration of 2–5 ms ● and less than 2 ms ▲.

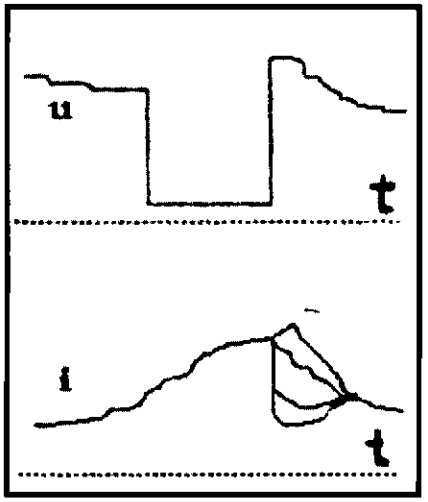

Fig. 6 — Schematic oscillographs of voltage and current at the arc reinitiating stage.

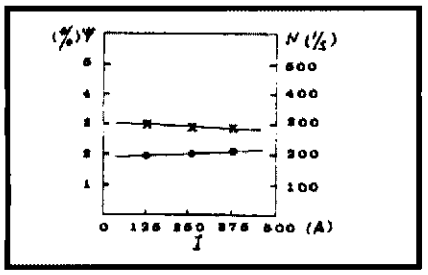

Fig. 7 — Effect of the current at the arc reinitiating stage upon the spatter coefficient X and the total number of short circuiting ●.

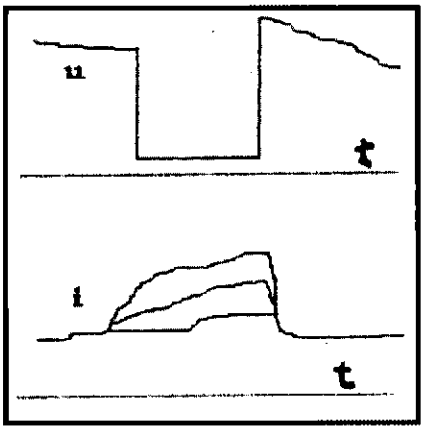

Fig. 8 — Schematic oscillograph of the current during the overall short circuiting process.

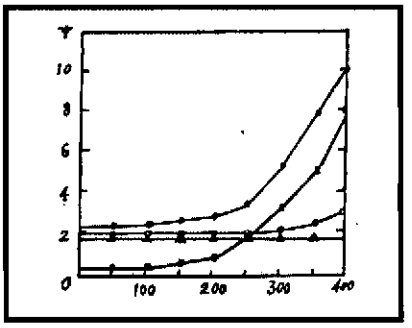

Fig. 9 — Effect of the current during the overall short circuiting process ●; effect of the current at arc reinitiating stage ▲; effect of the current at the beginning stage ○; effect of the current at the short circuit breakage stage ▮ upon the spatter coefficients.

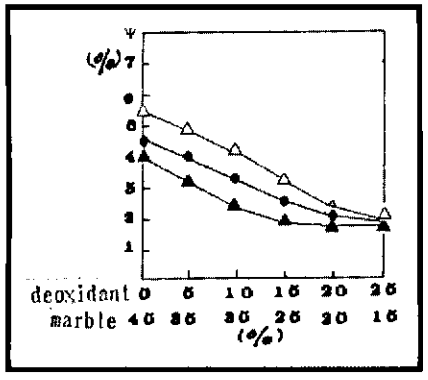

Fig. 10 — Effect of the oxygen potential in coverings upon the spatter coefficients produced by basic electrodes: Δ H08 core wire, ● H08Mn core wire, ▲ H08 Mn_2Si core wire.

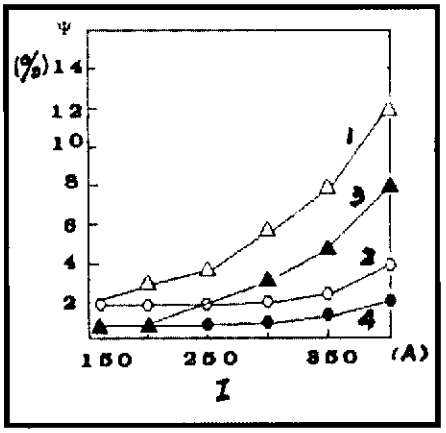

Fig. 11 — Combining effect of the short circuiting current and the oxygen potential on the spatter coefficients of electrodes with ratios of marble to deoxidant 40:0 Δ and 15:25 ○. The effect of the short circuiting current alone is shown by ●. The effect of the gas explosion alone is shown by ▲.

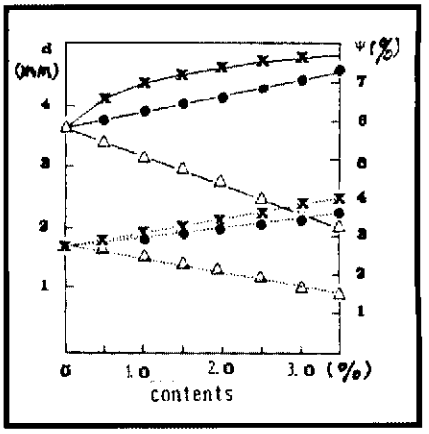

Fig. 12 — Effect of rare earth metal additives on the spatter coefficient shown by solid lines and diameters of metal bridges just prior to breakage shown by dotted lines X oxide of lanthanum, ● mixed oxide of rare earth metal, Δ Yttrium alloy.

ages, respectively, on the left side of the pictures.

Figure 14 shows some examples of the metal drop transfer processes taken by x-ray, back-light, high-speed photography. The middle Fig. 14 shows a bubble formed in a metal drop transferring from the electrode. The right Fig. 14 shows a bubble forming and evolving from the weld pool and causing spatter.

Discussion

The current at the stage of short circuit breakage is the prevailing parameter determining the spatter quantity.

As shown in Fig. 5 in the region below 300 A, the current at the beginning stage of a short circuit (within 4.5 ms) had no effect on the spatter quantity. When that current increases higher than 300 A, spatter increases correspondingly. Since under normal SMAW with an appropriate current surge dI/dt the current at the beginning of the short circuiting is less than 300 A, it is not considered to be the prevailing factor determining spatter production. From the same diagram, it is found that the number of instantaneous short circuiting increases linearly with the current at the beginning of a short circuit, but it does not cause an increase in spatter, especially in the region below 300 A.

As shown in Fig. 7, a current up to 400 A at the arc reinitiating stage after a short circuit raises the total number of short circuits a little, but had no effect on the spatter quantity. This means that under normal SMAW conditions, arc reinitiation is not the cause of spatter.

The effect on the spatter coefficient, caused by the current at the short circuit breakage stage, is shown by a curve in Fig. 9. This curve is calculated using the spatter quantities caused by increasing the current during the overall short circuiting period, minus that caused by increasing the current at the beginning of a short circuit and at arc reinitiation. From this curve, it is found that the prevailing effect on the spatter is caused by the current at the short circuit breakage stage. With increasing that current, the spatter quantities increase significantly. In Fig. 5 the increase in the spatter coefficient corresponds with the number of short circuits with a duration of 2–5 ms. It is due to that the current increase at the beginning stage of short circuits was set in a duration of 4.5 ms. For short circuits lasting 2–5 ms, this increase in current may be sustained to the breaking stage, thus increasing spatter. From this result, it can be concluded that among parameters of shielded metal arc welding (SMAW), controlling the short circuiting current at the moment of metal bridge breakage is

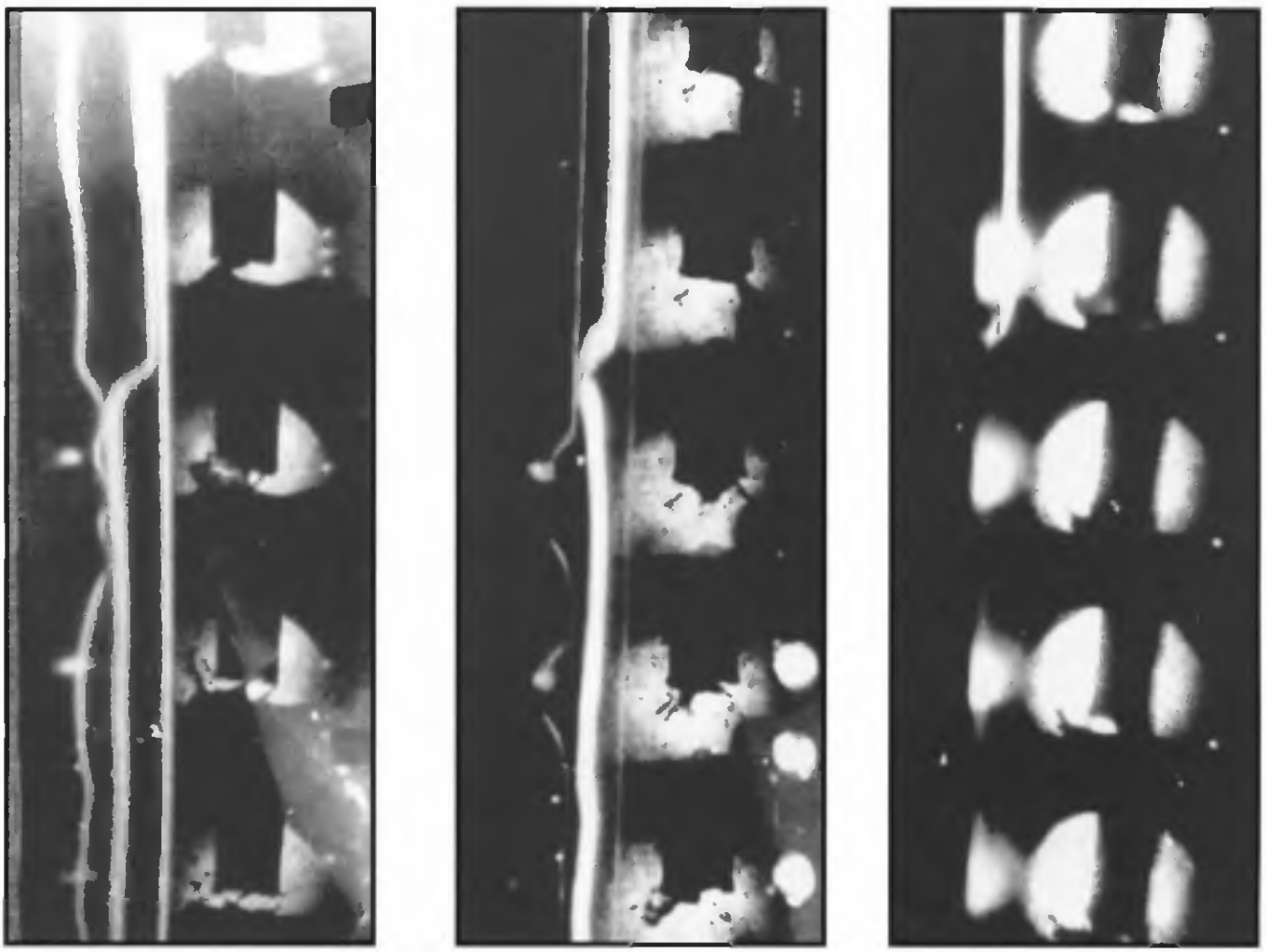

Fig. 13 — Typical processes of short circuit breakage taken by laser back-light, high-speed photography (200f/s). On right side is the main image of the liquid metal bridge and the process of breaking (time sequence is from upper to lower). On left side, the moment the short circuit breaks, the arc voltage jumps from the short circuiting voltage to the arc voltage, as shown by the thick line. The arc sound oscillograph vibrates violently, shown by the thinner line, as the explosion occurs at that moment. The light spots appear after that moment showing the reinitiation of the arc.

the most important one for decreasing spatter production.

The main process resulting in the spatter is the CO gas explosion. High current at this moment enhances this process and enlarges its effect.

In Fig. 12, the diameters of the metal bridges measured just prior to short circuit breakages increase with increasing rare earth metal agent contents. Spatter quantity variation coincides with that of diameters of the metal bridge. According to the electric explosion viewpoint, the spatter is caused by a high density of short circuiting current which overheats the metal bridge. It can, therefore, be concluded that the thinner the metal bridge, the higher the current density and the heavier the spatter. However, the experimental results in present work run counter to this conclusion. So the electrical explosion is not the main process of the spatter produced in SMAW with basic electrodes.

Figure 11 shows the experimental results of the combining effect of oxygen potential and the short circuiting current upon spatter. The electrode with a ratio of marble to deoxidant of 40:0 in the covering represents electrodes with high oxygen potential. Curve 1 presents the spatter produced when it is welded with various short circuiting currents. The electrode with ratio of marble to deoxidant content of 15:25 has a very low oxygen potential, and the spatter produced by it (shown by Curve 2) can reasonably be assumed to be caused by an electric effect. If 2% is taken to be an intrinsic spatter coefficient caused by random factors, Curve 4 in Fig. 11(by subtracting 2% from Curve 2) represents the spatter caused by increasing the short circuiting current only. Curve 3 is obtained by subtracting 2% of intrinsic spatter and subtracting Curve 4, the spatter caused by electrical effect, from Curve 1. It is taken as the spatter caused by the explosion of CO gas at various short circuiting current levels. It is apparent that the spatter quantity caused by gas explosion (Curve 3) is much higher than that caused by increasing the short circuiting current alone (Curve 4). Curve 3 also shows a significant increase in spatter with an increasing of short circuiting current, which means that the high short circuiting current enhances the gas explosion and enlarges its effect on spatter. Since under normal SMAW conditions the short circuiting current is about 250 A, the spatter caused by sole electrical effect is low (Curve 4). The high spatter shown by Curve 1 is caused mainly by the gas explosion.

Figure 12 shows that the rare earth metal oxides increase spatter, however, the rare earth metal alloys decrease the spatter. This phenomenon is consistent

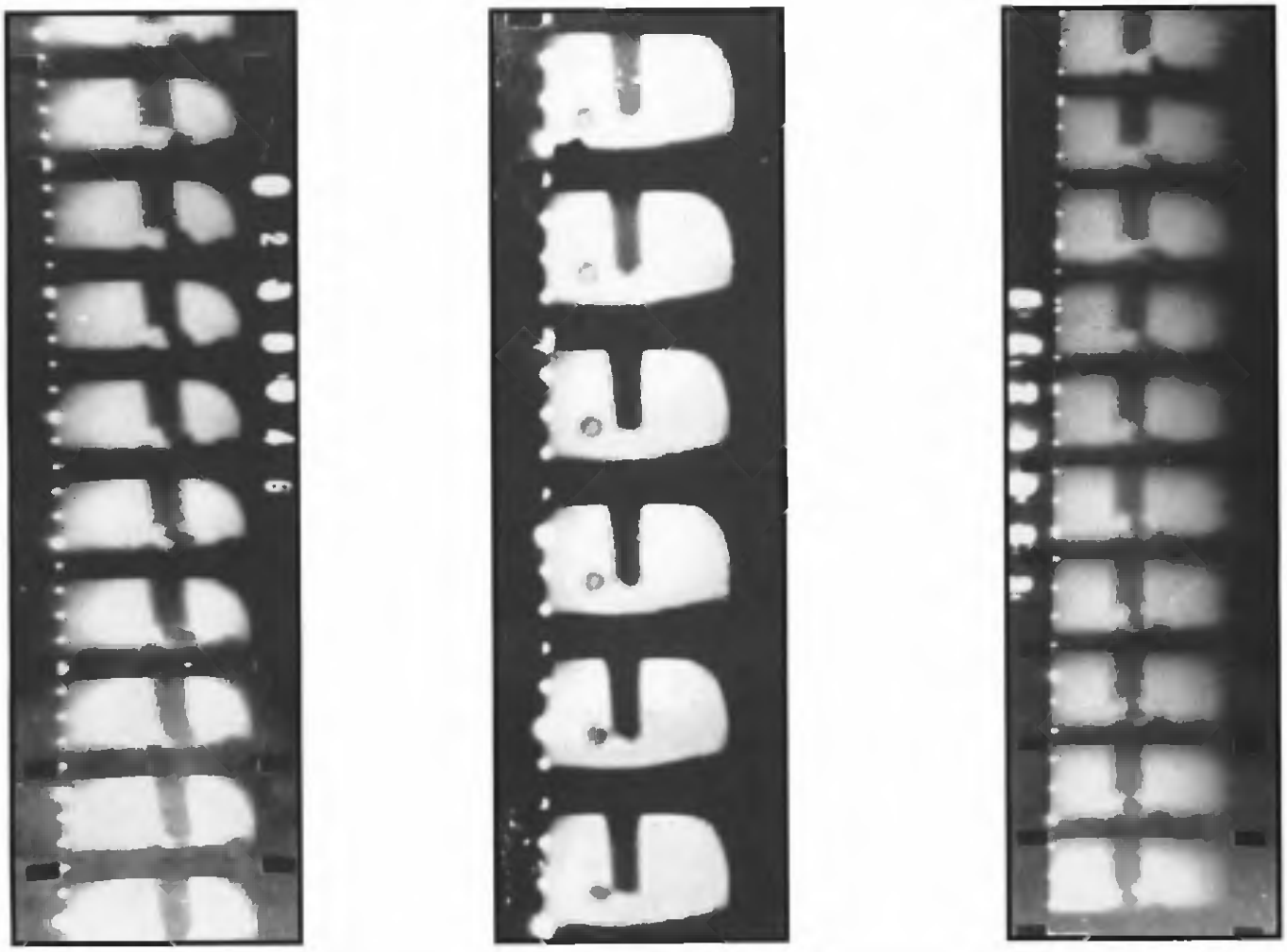

Fig. 14 — Metal transfer processes taken by x-ray, back-light, high-speed photography (time sequence is from lower to upper). Left figure: metal transfer without explosion; middle figure: a gas bubble formed in a transferring metal drop; right figure: a gas bubble forming and evolving from the weld pool.

with the viewpoint that CO gas is the main factor causing spatter. In Fig. 13, the spatter processes caused by gas explosion were apparently identified by using laser back-light high-speed photography. This diagram shows that the metal bridges of short circuits are broken by gas explosions. This can explain the results shown in Fig. 12. When the rare earth metal oxides content increases, the oxygen potential increases, the gas explosion occurs at an earlier stage of necking of the metal bridge. The metal bridge diameter is thicker at the moment of explosion and the spatter is higher. When the rare earth metal alloys increase, the oxygen potential decreases. The gas explosion occurs at a later stage of necking with a thinner bridge and causes less spatter. The phenomenon of gas bubble formation and evolution from the melted metal drop and the weld pool are illustrated further by x-ray high-speed photography in Fig. 14. The mechanism of spatter caused by the gas explosion is thus identified by direct observation.

On the basis of this result, it can be concluded that decreasing the oxygen potential in the covering of basic electrodes is of prime importance when designing an electrode to produce minimum spatter.

Conclusion

1) The main process causing spatter when welding with basic electrodes is the CO gas explosion at the moment of short circuit breakage, and the increase in current at this moment significantly enhances this process. Decreasing the oxygen potential in the covering of basic electrodes is of prime importance when designing a basic electrode to produce minimum spatter.

2) Among all of the parameters for SMAW with basic electrodes, the current at the short circuit breakage stage is the prevailing factor determining the spatter quantity. Controlling this current is of prime importance in decreasing the spatter quantity.

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