Comparison of Metal Transfer Behavior in Electrodes for Shielded Metal Arc Welding

X. Xu, S. Liu, and K. S. Bang

Abstract

Metal transfer behavior of three shielded metal arc welding electrodes, AWS E11018, E6013 and E6010, were investigated through the characterization of size distribution of droplets and measurement of arc voltage signals. Of the three electrodes, E11018 electrode showed the largest droplet size with the smallest amount of spatter, while E6010 electrode showed the smallest droplet size with the largest amount of spatter. Even though E11018 electrode showed a good agreement between the frequencies of voltage drop in FFT processed voltage signals and the transfer rate of droplets, E6013 and E6010 electrodes showed weaker correlation because of their dominant explosive transfer behavior. The type of cathode used and electrode baking time also influenced the metal transfer behavior. Compared to bead-on-plate welding using steel plate as a cathode, welding on a water-cooled copper pipe showed less short-circuiting and higher melting rate in all electrodes because of higher arc potential and/or anode drop. When baked for a long time, E6010 electrode showed much more stable arc with less short-circuiting and explosion due to the loss of gas formation ingredients.

Key Words : SMAW, Electrodes, Metal transfer, Arc voltage, Spatter, Baking time.

1. Introduction

As metal transfer of welding consumables is one of the major factors controlling weld quality, the knowledge of how it is affected by the welding conditions is important for welding control and process automation, as well as in the development of improved consumables. These requirements have led to an increase of interest in research efforts to determine and control the metal transfer mode during welding. Metal transfer can be observed by direct and indirect methods. Examples of direct methods are high-speed cinematography and high-speed video technology.[1,2] Indirect methods rely basically on the variations of arc current and voltage with the transfer of each metal droplet.[3,4] The arc signals are recorded and analyzed to determine the transfer behavior. Attempts have also been made to use acoustic signals to monitor metal transfer.[5] Due to its simplicity and large sampling capacity, arc-sensing methods have been used widely. Recognizing that droplet detachment from the electrode tip in gas metal arc welding (GMAW) causes a variation of arc voltage, Liu, Siewert and Lan[3] calculated voltage fluctuation as the difference between the voltage peak and valley from the voltage signal and established a set of criteria of voltage fluctuation for different metal transfer modes. Wang, Liu and Jones[4] monitored the electrode arc signals of flux cored arc welding (FCAW) and processed them using the fast Fourier transform (FFT) technique to characterize metal transfer modes in FCAW. They

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identified the characteristic spectral frequencies corresponding to different metal transfer modes and showed that both arc voltage fluctuation and characteristic frequencies of the FFT spectra were adequate to distinguish metal transfer modes in FCAW.

Because the presence of flux covering in an electrode complicates significantly the metal transfer in shielded metal arc welding (SMAW), studies on metal transfer in SMAW are relatively few. Several models were proposed to explain metal transfer in bare electrode and covered electrode. Conrady6) proposed that welding with a bare electrode using straight polarity and in an overhead position, metal transfer was affected by the cathode spot. The pressure of cathode spot would cause the surface of the droplet to oscillate and eventually transfer by short-circuiting. Larson7) extended the model to include the effect of a gas bubble inside the molten electrode tip. As the bubble expanded, transfer of the droplet would occur by explosion of the droplet or short-circuiting. Systematic research has been carried out in one of the authors' lab to investigate the effect of covering of an electrode on the metal transfer. Brandi, Taniguchi and Liu8) observed three major types of metal transfer modes, explosive, short-circuiting, and slag-guided, in welding with E6011, E6013 and E7018 electrodes by studying size distribution of droplets collected. Pistorius and Liu9) processed the arc voltage signals of E6010, E6013 and E7018 electrodes in different ways and showed that the histogram of the arc voltage provided a useful visual summary of the behavior of the arc. They also showed the metal transfer behavior changed significantly as the electrode was consumed. As a part of the systematic research on metal transfer of SMAW electrodes, this work was carried out to investigate the relationship between the droplet size distribution and arc voltage signals in E6010, E6013, and E11018 electrodes. The effects of cathode type and electrode baking time on the metal transfer behavior were also studied.

2. Experimental procedure

Three commercial AWS E11018 (basic), E6013 (rutile), and E6010 (cellulosic) grade electrodes with diameter of 3.2mm were used in this experiment. As it was shown that the metal transfer behavior of an electrode is influenced by baking temperature, 10 all electrodes were baked at a constant temperature of 180℃. While this temperature is high for cellulosic electrode, it was chosen to bake the three electrodes at a uniform temperature. Baking time was 24 hours. Automatic SMAW (DCEP) was performed using a Hobart power source (CYBER-TIG). As shown in Fig. 1, welding arc was struck against a water-cooled copper pipe that was suspended above a water tank and the droplets that fell into the different bins of the tank during welding were collected. After removing the flux magnetically, the droplets were classified into different size ranges using the Tyler standard sieve numbers. The number of collected droplets in each sieve was determined by an image analysis system. Welding current and arc voltage varied between 100 to 150A and 22 to 32V, respectively. Welding speed was fixed at 2.5mm/s.

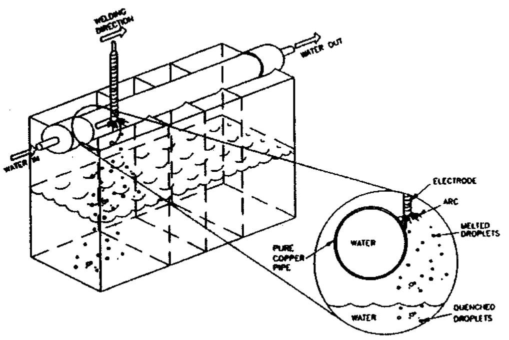


Fig. 1 Schematic illustration of experimental apparatus used to weld on a water-cooled copper pipe

Using a high-speed data acquisition system, arc voltage signals during welding were monitored by measuring the voltage between the electrode and the copper pipe. Data sampling frequency was 3kHz. Frequency spectra were determined from the arc voltage signals using fast Fourier transform (FFT) to determine the frequency responsible for the metal transfer. Bead-on-plate welding using A-36 steel plate

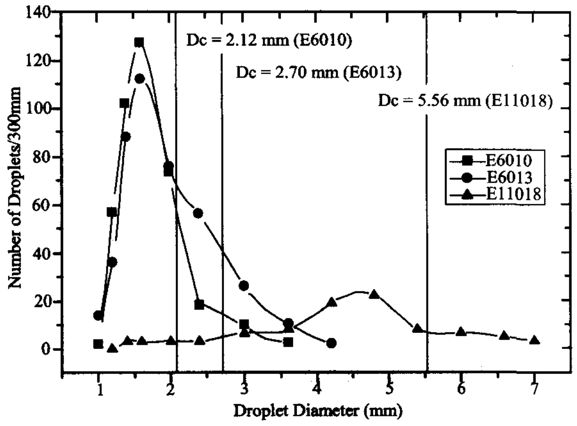


Fig. 2 Size distribution of collected droplets larger than 1mm in diameter. Welding conditions were 100A/23V, 100A/22V, and 100A/29V for E11018, E6013, and E6010, respectively

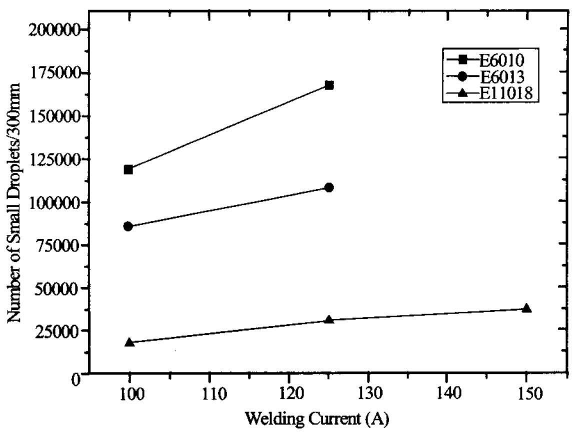


Fig. 3 Variation of calculated total number of fine droplets as a function of welding current. Welding conditions were 100A/23V, 125A/26V, and 150A/28V for E11018; 100A/22V and 125A/25V for E6013; 100A/29V and 125A/34V for E6010

as the cathode was also performed to investigate the effect of cathode type (non-melting copper pipe or steel plate) on the metal transfer behavior.

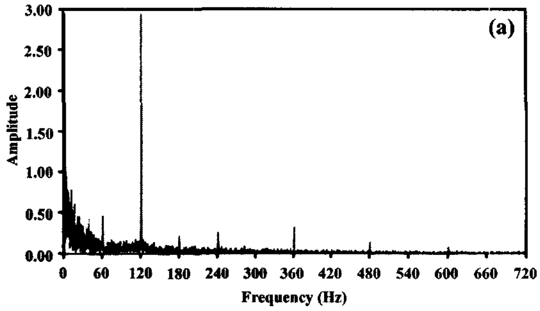
3. Results and discussion

3.1 Droplet size distribution and arc voltage signals

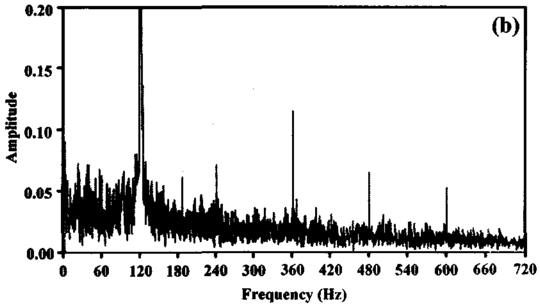
To compare the size distribution of droplets between electrodes, droplets were collected during welding and melting of 300mm of the electrodes. While relatively lager droplets tended to fall in bins in a water tank directly below the arc, smaller ones had a higher degree of scatter and were collected mostly in bins farther away from the arc. For the accurate determination of the number of collected droplets, droplets only larger than Tyler standard sieve number 28 (0.60mm) were counted. Fig. 2 shows the results of welding at 100A/23V, 100A/22V, and 100A/29V for E11018, E6013, and E6010, respectively. A single parameter termed "characteristic diameter," Dc, was determined for each electrode. It takes into consideration the number and total volume of the droplets accumulated in each size class. Dc is a common parameter used in particulate processing to describe a population of particles. The detail of the calculation was shown in a previous publication of one of the authors.[8] The calculated Dc were 5.56, 2.70 and 2.12mm, for E11018, E6013, and E6010 electrode, respectively. Of the three electrodes, E6010 electrode resulted in the smallest droplets, while E11018 electrode produced the largest. This result confirms previous experimental results, in which cellulosic type electrode showed the smallest droplets, while basic type electrode produced the largest.[8,9] Meanwhile, the transfer rate of droplets, which is the ratio of total number of droplets to the welding time, was the lowest in E11018 electrode as 1.02/s, while the highest in E6010 electrode as 4.9/s.

Fig. 3 shows the variation of number of fine droplets (Ø<0.6mm) as a function of welding current. After measuring the weight of droplets and assuming that all droplets are solid sphere, the number of droplets was calculated. The number of droplets increased with an increase of welding current for all electrodes. However, at the same current level, E6010 electrode showed the largest droplet number, while E11018 electrode shows the smallest. For example, the numbers are about 18000, 85000, and 118000, for E11018, E6013, and E6010 electrode, respectively, at welding current of 100A. According to Brandi, Taniguchi and Liu,[8] if the number of fine droplets is assumed to be the total amount of spatter during welding, E11018 electrode produced the smallest amount of spatter while E6010 electrode produced the largest amount. Therefore, it can be seen from above results that a basic type electrode shows larger size droplets with small amount of spatter, while a cellulosic type electrode produces smaller size droplets with large amount of spatter. Additionally, E11018 electrode exhibited longer arc length than E6013 electrode during welding.

The variation of voltage in each electrode during welding is related to the metal transfer behavior observed above. When a molten metal detaches from the electrode tip, a voltage drop occurs due to the change of arc length. An attempt was made in this experiment to correlate the frequency of these voltage drops and the transfer rate of droplets observed. However, due to several noises in the voltage signal such as line voltage, voltage fluctuations as a result of weld pool oscillation, and background noise, etc, it is difficult to characterize those voltage drops which are responsible for the metal transfer. To filter out the noises from the voltage signals, a spectral analysis using FFT technique was applied. The frequency spectrum was calculated from the voltage signal first, and then it was compared with the spectrum obtained from gas tungsten arc welding (GTAW), which involves no metal transfer. Fig. 4 (a) and (b) show FFT processed frequency spectra for SMAW (E11018) and GTAW, respectively. The welding conditions were 100A/23V for SMAW and 100A/21V for GTAW. Except for the characteristic frequency of the power source, multiples of 60Hz, the noises are distributed across the entire frequency domain in both spectra. However, main differences exist in the frequency range of 0-60Hz, where the amplitude is much higher in the E11018 electrode. Further expanding the signals shows that frequency band of 0-20Hz is most likely responsible for the metal transfer. After processing the voltage signals using a low-pass and a band-pass filter, the number of voltage drops was counted from the processed signals. Table 1 summarized the frequency of voltage drop in each electrode along with Dc and the droplet transfer rate discussed above in various welding conditions.



(a) SMAW with E11018 at 100A/23V



(b) GTAW at 100A/21V

Fig. 4 FFT frequency spectra of arc voltage signals

According to Table 1, the frequency of voltage drop and droplet transfer rate is almost identical for E11018 electrode. However, a considerable difference exists for E6013 and E 6010 electrodes. The frequency of voltage drop is higher than the droplet transfer rate. To investigate the reason for this difference in electrodes, random samples were collected from the most typical droplet diameter and polished to observe the porosity in the droplets. Fig. 5 shows that more porosity was observed in the droplets from E11018 electrode (A) than in the droplets from E6013 (B) and E6010 (C) electrodes. The covering of rutile (E6013) and cellulosic (E6010) electrodes typically consist of much more gas sources, like organics, than basic (E11018) electrode. Therefore, during welding, much more gas will be generated in the rutile and cellulosic electrodes than in the basic electrode. Part of these gases

Table 1 Summary of frequency of voltage drop, characteristic diameter and droplet transfer rate in various welding conditions

Electrode	Welding condition	Frequency of voltage drop (Hz)	Characteristic diameter, Dc (mm)	Droplet transfer rate (/s)
E11018	100A/23V	1.0	5.56	1.02
	125A/26V	3.3	3.64	3.18
	150A/28V	7.9	2.76	8.28
E6013	100A/22V	4.8	2.70	3.87
	125A/25V	8.9	2.24	5.27
E6010	100A/29V	13.8	2.12	4.90
	125A/34V	12.5	1.84	7.00

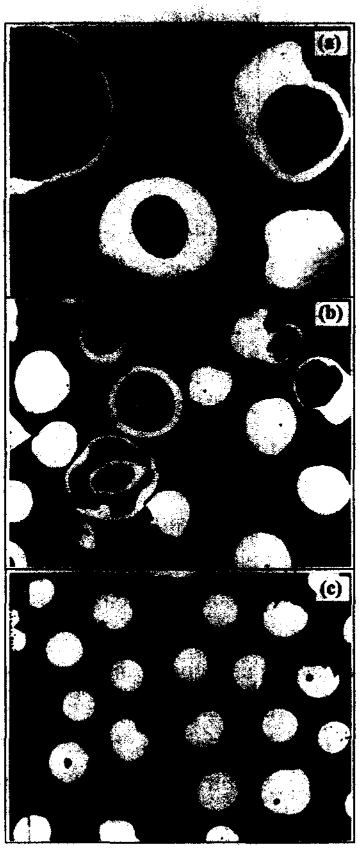


Fig. 5 Polished section of typical collected droplets
(a) E11018 at 100A/23V
(b) E6013 at 100A/22V
(c) E6010 at 100A/29V

may be incorporated into the molten metal and produce gas bubbles inside it. The bubbles may grow larger in the molten metal with further gas reaction from the flux. If the gas expansion force is large enough to overcome the surface tension, the bubbles will be released in an "explosion". Otherwise, the molten metal grows until it detaches as a globule or short-circuits with a weld pool, and quickly solidifies and entraps the gas inside the droplet to form porosity. In fact, a dominant explosive transfer mode in rutile and cellulosic type electrodes was reported in other studies.[8,11] Therefore, it is believed that as E6013 and E6010 electrodes have dominant explosive transfer mode in this experiment, they show a large amount of fine droplets (spatter) and give the discrepancy between the droplet transfer rate and the frequency of voltage drop in the arc voltage signal. On the contrary, as E11018 electrode has dominant globular and/or short-circuiting transfer mode, it shows a small amount of spatter with its droplet transfer rate matching well with the frequency of voltage drop. During welding, it was also observed that E6010 electrode produced much more gas than E6013 electrode. The higher gas expansion force of E6010 electrode caused a higher explosive rate than that of E6013, which explains the higher droplet transfer rate in E6010 electrode.

3.2 Comparison between the simulated and actual welding

Welding in the droplet collection experiments

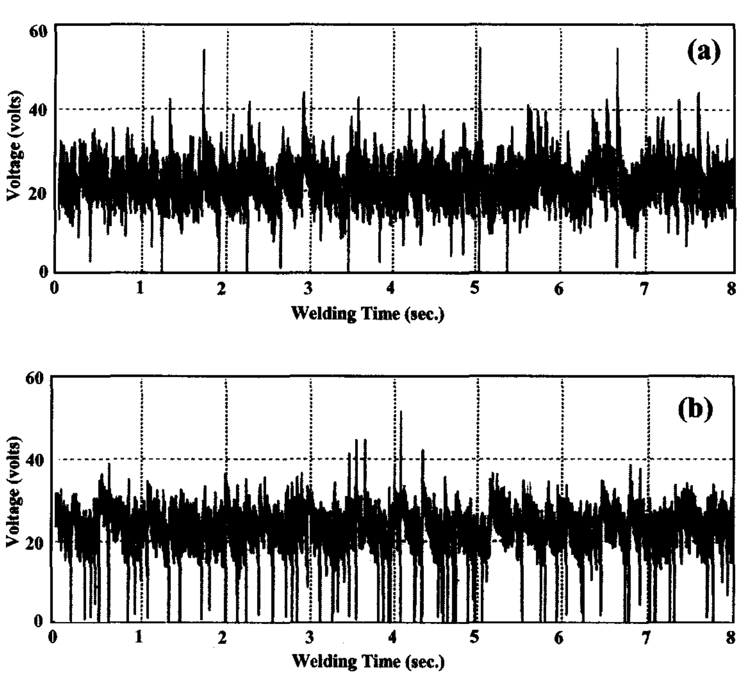


Fig. 6 Comparison of voltage signals during (a) the droplet collection experiment and (b) bead-on-plate welding when E6013 electrode was used

explained above is only a simulation of the actual welding in that it used a water-cooled copper pipe as a cathode. The different conditions from the actual welding may affect the reliability of the detection of the metal transfer behavior. To study the difference between the two cases, arc voltage signals during bead-on-plate welding using A-36 plate as the cathode were recorded. Fig. 6 compares voltage signals during the droplet collection experiment and bead-on-plate welding when E6013 electrode was used for example. Compared with the voltage signal in the droplet collection experiment (a), more short-circuiting was observed in the bead-on-plate welding (b). These results imply that shorter arc length is obtained in a bead-on-plate welding. In addition, it was also observed that the melting rate of an electrode was lower in a bead-on-plate welding. For example, at 100A/22V, the melting rate of E6013 electrode was 3.7mm/s in the bead-on-plate welding, while it was 4.0mm/s in the droplet collection experiment.

In DCEP welding on a steel plate, the current is carried in the cathode region mainly by the electrons. On the contrary, in the case of arcing on a water-cooled copper, it was suggested that the current in the cathode region is carried by the positive ions produced in the plasma and anode regions, therefore requiring higher arc potential and/or anode drop in order to provide sufficient positive ions.[12,13)] The increased arc potential causes an increase in arc length, and thus results in less short-circuiting in the droplet collection experiments. In addition, it is believed that the higher melting rate of electrodes in the droplet collection experiments is attributed to the increase of anode drop.

3.3 Effect of baking time of an electrode

Metal transfer behavior of an electrode is dependent on the baking temperature of the electrode. According to Wegrzyn,[10)] an acid electrode produced larger droplets when baked at high temperature, and showed much difficulty in overhead welding when baked at 750℃. He showed the loss of moisture and

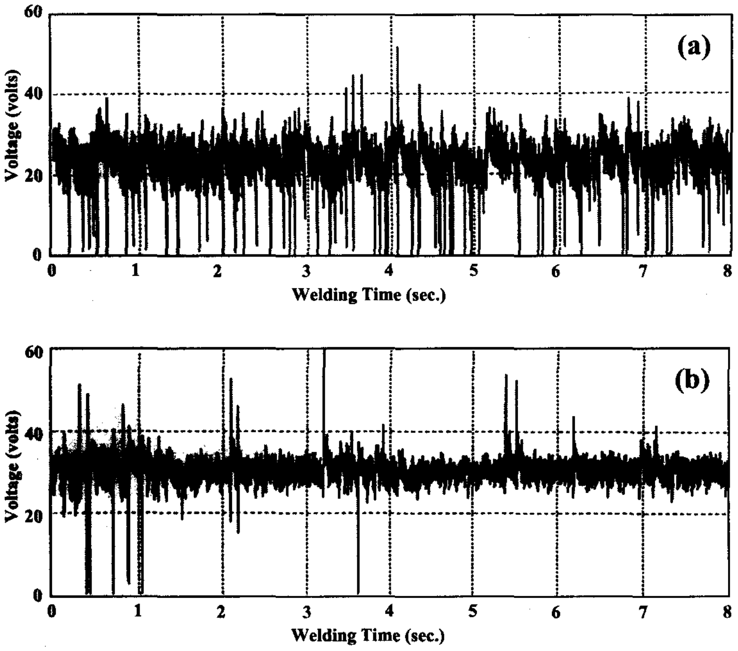


Fig. 7 Comparison arc voltage signals of E6010 electrodes that were baked for (a) 24 hours and (b) one month

loosely-bounded water of crystallization in the covering increased with an increase of baking temperature. As it is supposed that the content of moisture and water of crystallization in the covering is also influenced by the baking time, the effect of baking time on the metal transfer behavior was investigated in this experiment. Bead-on-plate welding was performed using electrodes baked at 180℃ for one month. Fig. 7 compares arc voltage signals of E6010 electrodes that were baked for 24 hours (a) and one month (b). Welding condition was 100A/29V. More stable arc with less short-circuiting or explosion was observed in the electrode baked for one month.

This observation indicates that long baking time, even at temperature as low as 180℃, has the same effect as high temperature baking. Similar to the high temperature baking, it is believed that the amount of gases from the covering is reduced in the long baking. This is supported by the observation that E6010 electrode, which has a large amount of gas formation ingredients, showed the most drastic change. The removal of gas formation ingredients increases the fraction of easier ionized metal vapor and makes more stable arc with reduced gas expansion force. Moreover, the decrease of the drag force acting on the droplets makes it difficult for the droplets to overcome the surface tension force.

4. Conclusion

1. Of the three electrodes, E11018 electrode showed the largest droplet size with the smallest amount of spatter, while E6010 electrode showed the smallest droplet size with the largest amount of spatter.

2. The frequency of voltage drop in FFT processed voltage signals matched well with the droplet transfer rate for E11018 electrode. However, it was higher than the droplet transfer rate for E6013 and E6010 electrodes because of the dominant explosive transfer of metal droplets.

3. Compared to bead-on-plate welding on a steel plate, welding on a water-cooled copper pipe showed

less short-circuiting and higher melting rate in all electrodes because of higher arc potential and/or anode drop in an arc column.

4. Similar to the baking at high temperature, long baking of electrodes, especially E6010, resulted in more stable arc with less short-circuiting and explosion due to the loss of gas formation ingredients.

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