ABSTRACT. Metal droplet transfer in flux cored arc welding (FCAW) was studied using electrical arc signals and droplets collected from the welding process. A large number of metal droplets from the FCAW experiments was collected. According to the size distribution of the droplets, several metal transfer modes could be identified amongst which spray transfer predominated. The electrical arc signals, in particular, voltage, were processed using the fast Fourier transform (FFT) technique. Characteristic spectral frequencies corresponding to different metal transfer modes were identified. The size distribution of the collected droplets correlated extremely well with these characteristic frequencies. The electrode melt rate, calculated using the characteristic frequencies identified from the FFT analysis, agreed closely with the measured melt rate. Results from the arc signal analysis and the FFT analysis showed that both arc voltage fluctuations ($\Delta u$) and characteristic frequencies of the FFT spectra were adequate to distinguish the different kinds of metal transfer modes in FCAW. Metal transfer mode maps, constructed using the two sets of results, were used to determine the optimal parameters for E71T-1, 1/16-in.-diameter electrode, and Ar-25%CO$_2$ shielding gas.


KEY WORDS

FCAW
Spray Transfer
Globular Transfer
Short-Circuiting Transfer
Voltage Fluctuation
Fast Fourier Transform
Operating Window
Droplet Size Distribution
Weld Pool
Arc Voltage Signals

Flux Cored Arc Welding: Arc Signals, Processing and Metal Transfer Characterization

Certain arc voltage signals are verified as indicators of transfer modes and thereby arc stability

BY W. WANG, S. LIU AND J. E. JONES

Introduction

Metal transfer can be described as the transport of molten droplets from the tip of a consumable electrode to the weld pool. According to the size and transfer characteristics of the molten droplets, different types of transfer modes can be defined. The complete IIW classification of metal transfer modes is shown in Table 1 (Ref. 1).

The size of a molten droplet depends on several forces that act on the electrode tip. The major forces include the Lorentz force, gravitational force, surface tension, and plasma flow-related drag force. The Lorentz force can be described as a force that causes necking and the detachment of a molten droplet from the molten electrode tip. The Lorentz force is a function of current density, and the effect of welding current on the metal transfer modes has been investigated (Refs. 2-6).

At low current density range, Lesnewich (Ref. 2) reported a transition current around 250 A for gas metal arc welding (GMAW) as shown in Fig. 1. The transition of current resulted in a large increase in droplet transfer rate and an abrupt size reduction of the molten droplets. More recently, Liu, et al. (Ref. 6), also observed a transition current at approximately 200 A for GMAW when voltage was maintained at about 26 V. Below the transition current, low-frequency short-circuiting transfer occurred, and above 200 A, spray transfer was observed. On the contrary, Ludwig (Ref. 4) observed no transition current within the range of 200 to 450 A.

At high current density range, from 500 to 1000 A for a 4.0-mm (5/32-in.) diameter solid wire, Watanabe, et al. (Ref. 5), reported a transition from streaming to globular transfer. The transition was continuous with respect to welding current and voltage. The continuous transition was actually shown by Liu, et al. (Ref. 3), as a mixed transfer, with the coexistence of spray, globular and short-circuiting transfer — Fig. 2.

All the studies above investigated the effect of welding current on metal transfer. However, voltage is extremely important when welding at high current densities because, due to metal vaporization, the repelling force that acts on the anode spot increases with arc voltage (Ref. 5). Liu, et al. (Ref. 3), observed that welding voltage can affect the relative...
Table 1 — IIW Classification of Metal Transfer Modes (Ref. 1)

<table>
<thead>
<tr>
<th>Designation of Transfer Type</th>
<th>Welding Process (examples)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 Free-flight transfer</td>
<td>low-current GMA</td>
</tr>
<tr>
<td>1.1 Globular</td>
<td>CO₂ shielded GMA</td>
</tr>
<tr>
<td>1.1.1 drop</td>
<td>intermediate-current GMA</td>
</tr>
<tr>
<td>1.1.2 repelled</td>
<td>medium-current GMA</td>
</tr>
<tr>
<td>1.2 Spray</td>
<td>high-current GMA</td>
</tr>
<tr>
<td>1.2.1 projected</td>
<td>SMA (covered electrodes)</td>
</tr>
<tr>
<td>1.2.2 streaming</td>
<td>short-circuiting GMA, SMA</td>
</tr>
<tr>
<td>1.2.3 rotating</td>
<td>welding with filler metal addition</td>
</tr>
<tr>
<td>1.3 Explosive</td>
<td>SAW</td>
</tr>
<tr>
<td>1.3.1 repelled</td>
<td>SMA, cored wire, electroslag</td>
</tr>
<tr>
<td>1.3.2 rotating</td>
<td></td>
</tr>
<tr>
<td>1.3.3 rotating</td>
<td></td>
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<tr>
<td>1.3.4 rotating</td>
<td></td>
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<tr>
<td>1.4.1 rotating</td>
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<tr>
<td>1.4.2 rotating</td>
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<tr>
<td>1.4.3 rotating</td>
<td></td>
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<tr>
<td>1.5 Stream</td>
<td></td>
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<td>1.5.1 stream</td>
<td></td>
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<tr>
<td>1.5.2 stream</td>
<td></td>
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<tr>
<td>1.5.3 stream</td>
<td></td>
</tr>
<tr>
<td>1.6 Explosive</td>
<td></td>
</tr>
<tr>
<td>1.6.1 repelled</td>
<td></td>
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<tr>
<td>1.6.2 rotating</td>
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<tr>
<td>1.6.3 rotating</td>
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<td>1.7 Stream</td>
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<td>1.7.1 stream</td>
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<td>1.7.2 stream</td>
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<tr>
<td>1.7.3 stream</td>
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<tr>
<td>1.8 Explosive</td>
<td></td>
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<tr>
<td>1.8.1 repelled</td>
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<tr>
<td>1.8.2 rotating</td>
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<tr>
<td>1.8.3 rotating</td>
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<tr>
<td>1.9 Stream</td>
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<td>1.9.1 stream</td>
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<td>1.9.2 stream</td>
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<tr>
<td>1.9.3 stream</td>
<td></td>
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<tr>
<td>2 Bridging transfer</td>
<td></td>
</tr>
<tr>
<td>2.1 short-circuiting</td>
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<tr>
<td>2.2 bridging without interuption</td>
<td></td>
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<tr>
<td>3 Slag-protected transfer</td>
<td></td>
</tr>
<tr>
<td>3.1 flux-wall guided</td>
<td></td>
</tr>
<tr>
<td>3.2 Other modes</td>
<td></td>
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</table>

percent of each metal transfer mode present, as shown in Fig. 3. With increasing welding voltage, short-circuiting transfer increased, followed by a substantial decrease. Spray transfer, on the other hand, increased with increasing voltage and predominated at higher voltages. Despite the gradual decrease observed, globular transfer was present throughout the entire voltage range (Ref. 3).

Compared with GMAW, FCAW is more complicated due to the flux/metal interactions. Since the metal cross-section area of a FCAW electrode is much smaller than that of a GMAW wire of the same diameter, FCAW is conducted at much higher current densities. Thus, welding parameters are extremely important in determining the metal transfer modes in FCAW. In this research, the electrode arc signals of FCAW were monitored and processed using the fast Fourier transform technique to characterize metal transfer modes. Results from the arc analysis were compared with actual transferred droplet data to determine the applicability of arc signals as indications of arc stability and metal transfer.

Experimental Procedure

A PUMA 560 welding robot equipped with a SCR, three-phase Linde VI-450 SS constant-potential power source was used to perform FCAW with an AWS E71T-1, 1/16-in. (1.6-mm) diameter electrode. The welding robot CPU provided command signals to an interface unit that controlled the welding parameters precisely and consistently. In addition, the robot was position-calibrated before each welding experiment, therefore, the contact-tube-to-work distance (CTWD) was maintained constant at 3/4 in. (0.19 mm). The welding gun work angle was set at 45 deg and the lead angle was 0 deg. The setting resulted in the best droplet collection. The shielding gas was a mixture of 75% Ar + 25% CO₂.

To characterize the metal transfer behavior in FCAW, a metal droplet collection system was developed. A thin-wall, water-cooled copper tube was built as the cathode for the welding arc. Metal droplets that impinged on the copper cathode were quenched and collected in a small, water-filled chamber. The molten droplets were later classified by size to determine the three predominant transfer modes: spray, short-circuiting, and globular. Meanwhile, the electrical arc signals were recorded using a high-speed data acquisition system, with a 7.3-kHz sampling rate, as shown in Fig. 4. The system also had a low-pass filter with a cut-off frequency of 2 kHz and a high-pass filter with a 60-Hz cut-off frequency to minimize the high frequency and background noise, respectively, including line power oscillations.

The number of droplets collected and the size distribution were determined both manually, under an optical stereomicroscope, and automatically, using a quantitative image analyzer, which had a size resolution limit of 0.1 mm and a ±2% accuracy. As configured, the system exhibited good repeatability.

To further characterize the collected droplet size distribution, a high-speed video system was used to record the welding arc and metal droplet transfer at 1000 frames per second. It was found that FCAW molten droplet transfer resembled that of GMAW. Based on this evidence, the size classification for GMAW was applied to FCAW, i.e., if a droplet diameter was smaller than that of the wire...
electrode, it was considered a spray transfer; if a droplet diameter was larger than that of the wire, it was regarded as a globular transfer; and if a droplet touched the weld pool, it was recognized as a short-circuiting transfer. The welding process was characterized accordingly: if the number of one particular type of transfer increased, its significance and contribution to the arc behavior also increased.

Extensive welding experiments, as shown in Fig. 5, were carried out to collect arc signal data, which were later processed using a computer. Each record consists of approximately one second of arc data. The welding experiments were conducted at various travel speeds ranging from 2.5 to 6.4 mm/s (6 to 15 in./min).

Results and Discussion

FCAW Spray Transfer and Droplet Size Distribution

To characterize spray transfer in FCAW and correlate droplet size distribution with transfer rate, the number of droplets collected at preset welding parameters to maximize spray transfer was counted under a stereomicroscope. The average transfer rate was determined to be approximately 2100 droplets per second. This number is significantly higher than those reported for other arc welding processes (Ref. 7). The discrepancy can be explained by the methods followed in droplet transfer rate determination. Arc signal fluctuations and optical monitoring, commonly used in arc studies, both present resolution problems. Not only difficult to resolve optically, small droplets also cause minimum voltage and current variations, and cannot be easily detected using the two techniques. In this investigation, the size of the droplets varied significantly. Most droplets were beyond the resolution of the computer screen of the image analysis system, that is, smaller than 0.1 mm. As an example, the image analyzer could only resolve 20% of the over 40,000 droplets collected from one welding experiment and counted under a stereomicroscope. With few exceptions, all droplets were smaller than the electrode diameter. As such, it was more appropriate to separate the few large droplets (whose diameters were greater than that of the electrode) from the numerous smaller ones to allow for more accurate recognition by the image analyzer system. The droplet size distribution is shown in Fig. 6. Since metal droplets of sizes larger than the diameter of the electrode were also observed, even though in a limited number, mixed globular and spray transfer occurred. The relatively small number of globular droplets indicated that the transfer occurred predominantly in the spray mode.

Correspondence between Droplet Size Distribution and Arc Voltage FFT Spectra

From the “predominantly spray transfer” welding experiment — 23 V, 146 A, 52.9 mm/s (125 in./min) wire feed speed, 5.1 mm/s (12 in./min) travel speed as indicated in Figs. 6 and 7 — three recognizable droplet size groups were identified from the size distribution diagram — Fig. 6:

Peak 1: 0.102–0.151 mm
Average diameter: 0.126 mm
Peak 2: 0.248–0.297 mm
Average diameter: 0.273 mm
Peak 3: 0.393–0.443 mm
Average diameter: 0.419 mm

Droplets that have diameters within these three ranges predominated the transfer. Since the size of molten droplets affects the arc voltage fluctuation, droplets from these three size classes will exert greater influence on the electrical arc signals during welding. Provided that the overall electrode melt rate is maintained constant, then the three ranges of droplet size modes should also result in three transfer rates correspondingly. It is expected that the arc voltage signals would contain the transfer rate information. Indeed, spectral analysis using the FFT technique showed the individual arc voltage frequency components with three predominant frequency components at 290, 146 and 95 Hz — Fig. 7.

It was found that the number of the larger droplets transferred by
short-circuiting and/or globular transfer (with diameters greater than the electrode diameter) and collected per arc time was far less at 95, 140, and 290 Hz. It was obvious that these three frequencies were not the harmonics of the short-circuiting and/or globular transfer. On the other hand, these frequencies did not correspond to the line power harmonics which were multiples of 60 Hz (note that a low-pass filter was built in the circuit to minimize these harmonics). In addition, if these three frequencies were originated from the line power signals, their presence should be noted consistently in other spectra for different welding parameters obtained in this work. However, they were not observed, indicating that the three frequencies must have been generated by the effect of spray transfer.

As demonstrated above, even though metal droplets of different sizes were transferred throughout welding, droplets of three particular sizes (0.126 mm, 0.273 mm and 0.419 mm) were transferred regularly at the three rates of 290, 140 and 95 Hz. A more detailed discussion on the FFT technique is presented later in the next section.

In addition to the correlation with metal droplet size, the metal transfer rates must be related with the electrode melting rate, which could be determined experimentally. First, the weight per inch tubular-steel wire was determined after thoroughly removing the core flux. Then, markings were made on the welding wire to indicate the length of wire consumed. After a controlled arc time, the wire linear consumption was determined. Finally, the melting rate of 0.545 g/s was calculated by multiplying the experimentally determined weight per inch with the length consumed per second.

Calculations using the three characteristic transfer rates, i.e., 95, 140 and 290 Hz, were also made to estimate the melt rate. Assuming that each of the three transfer rates corresponded to one mass group, the mass transfer rate could be derived as the product of mass per droplet (i.e., average droplet volume multiplied by the steel density of 7.8 g/cm³) and the transfer rate. Therefore, the following equations were obtained:

1. mass transferred at 290 Hz:
   \[ \text{Mass 1} = \frac{\pi(0.419^2 - 0.126^2)}{6} \times 7.8 \times 290 \, \text{g/s} \]

2. mass transferred at 146 Hz:
   \[ \text{Mass 2} = \frac{\pi(0.273^2 - 0.126^2)}{6} \times 7.8 \times 146 \, \text{g/s} \]

3. mass transferred at 95 Hz:
   \[ \text{Mass 3} = \frac{\pi(0.126^2)}{6} \times 7.8 \times 95 \, \text{g/s} \]

4. large size droplets:
   \[ \text{Mass 4} = \frac{9.920 \times 19.6}{19.6} = 0.506 \, \text{g/s} \]

5. total mass transferred:
   \[ M = \text{Mass 1} + \text{Mass 2} + \text{Mass 3} + \text{Mass 4} = 0.549 \, \text{g/s} \]

where Mass 4 was the contribution from the few large droplets (as previously defined). The total calculated deposition rate was 0.549 g/s. The extremely small difference between the two values, that is, 0.549 g and 0.545 g, confirms the initial assumption that 290, 146 and 95 Hz represent the predominant transfer rates in the experiment.

Notice that the predominant transfer mode as perceived by arc signals does not necessarily correspond to the predominant mass transfer mechanism. Many larger droplets were found to be hollow, which agreed with the literature (Ref. 8). Irregular transfer events with large droplets such as short-circuit or globular transfer could be responsible for a respectful amount of mass transferred across the arc. Regular, uniform spray...
a respectful amount of mass transferred across the arc. Regular, uniform spray transfer, on the other hand, provided a steady but relatively small amount of metal deposition. In addition, metal transfer in FCAW did not occur in a single mode. Spray transfer basically accompanied all other modes. Therefore, the transfer rate for a particular droplet transfer mode, i.e., the number of events accompanied by voltage fluctuation signals of a similar magnitude, had no direct linear relationship with the overall mass transfer rate in the welding process. Instead, the predominant transfer modes represented more adequately the arc behavior and stability. Therefore, the correlation between the two sets of data from droplet collection and arc signal processing can be considered valid. The correlation indicated that the droplets of 0.1263-mm diameter were transferred at 290 Hz, droplets of 0.273-mm diameter at 146 Hz, and droplets of 0.419-mm diameter at 95 Hz.

As for the very tiny droplets (< 0.102 mm), their transfer rates were obviously higher than 290 Hz. However, the small sizes of these droplets are not expected to cause noticeable fluctuations of the arc signals. As a result, no significant higher frequency (> 290 Hz) peaks are expected in the FFT spectrum.

Based on the above discussion, the FFT technique exhibits a unique capability in distinguishing the metal transfer behavior in FCAW. The typical or predominant frequencies in the amplitude-frequency spectra will be used to correlate arc signal fluctuations with metal transfer behavior.

**Metal Transfer Δu Criteria**

Arc voltage changes with arc length. A small droplet transfer, such as a spray transfer featuring a small arc length fluctuation, results in a small arc voltage fluctuation, and a large droplet, such as a globular transfer with large arc length fluctuation, results in a large arc voltage fluctuation. Hence, arc voltage fluctuations, Δu, have been used as criteria to distinguish metal transfer modes (Ref. 3). To establish the Δu criteria for FCAW, background noise caused by the welding system must be eliminated. Thus, the open-circuit voltage signals of the welding system at 40 V was collected and examined. It was found that the voltage fluctuations were smaller than 0.3 V. Since the maximum voltage setting in the experimental program was 40 V, any voltage fluctuation less than 0.3 V was regarded as noise.

As a result of the formation and detachment of a droplet, the arc length decreases and increases periodically. Consequently, each transfer event corresponds to a voltage peak and a valley. A computer program was written to identify the peaks and valleys for each voltage-time trace and calculate the peak-valley voltage difference to acquire Δu for each transfer event. After comparing all the arc voltage signals collected in the time domain with the background noise signal, it was concluded, and verified by the droplets collected, that the characteristic Δu of short-circuiting mode is 10 V. All arc voltage fluctuations greater than 10 V can be characterized as short-circuiting events. Spray mode, on the other hand, presented smooth and uniform arc voltage trace in the time domain, with fluctuations ranging from 0.3 to 1 V. Thus, the Δu criteria for metal transfer in FCAW with an E71T-1 electrode with 75% Ar and 25% CO₂ shielding gas are suggested as follows:

- short-circuiting: Δu > 10 V
- globular: 1 < Δu < 10 V
- spray: 0.3 < Δu < 1 V
- noise: Δu < 0.3 V

Arc voltage signals from all experimental welds were examined using the Δu criteria for metal transfer mode determination. By identifying the individual droplet transfer events from the arc voltage traces, the relative percentage of each transfer mode, that is, number of transfer events of a particular mode divided by total number of transfer events, was calculated. In addition, a metal transfer mode map was determined — Fig. 8. Note that the results were consistent with those determined visually. In this metal transfer mode map, sc is short-circuiting, sp is spray and gb is globular.

**Metal Transfer FFT Characteristics**

In signal processing, Fourier transform is often used to transform a signal from time domain to frequency domain. In particular, FFT is extremely powerful in resolving complex signals such as welding voltage signals that usually contain multiple components such as arc voltage, line voltage, voltage fluctuations as a result of metal transfer and weld pool oscillation, background noise, etc.

The “3-db” rule is generally used in signal processing to recognize a valid signal. If the amplitude of a frequency component is 3 db higher than that of any other components in a ±50-Hz range, the amplitude is regarded as significant, and its corresponding frequency component, a signal. If the peak amplitude of a frequency component, higher than 400 Hz, is 3 db higher than that of any other frequencies in a ±100-Hz region, the amplitude is regarded as significant and its corresponding frequency component, a signal.

This modified 3-db rule, together with a 1.78-Hz frequency resolution and the Nyquist frequency of 7.3 kHz as the upper limit, were found to be able to distinguish the arc voltage FFT signals from the background noise. Because of the rapid and consistent amplitude decay of frequency signals higher than 1 kHz, 1 kHz was set as the upper limit frequency for plotting all spectra.

Since the transfer modes of the experimental welds have already been determined by the Δu criteria and visual observation, the characteristics of FFT spectra can also be used to verify the metal transfer modes.

Analyzing the FFT spectra and comparing them with actual arc observation, the following correlations were observed:
tion (arc stoppage), and metal transfer was irregular and inconsistent. Figure 9 illustrates the voltage-time plots of these welds. The corresponding FFT amplitude vs. frequency spectra were uniform without any particular high-amplitude frequencies — Fig. 10. Large voltage fluctuations (signal pulses) such as arc stoppage and short-circuiting transfer, when transformed to frequency domain, tend to "uniformize" the whole FFT spectrum, decreasing amplitudes at higher frequencies.

2) When over 10% globular transfer events occurred in a spray transfer "background," only one predominant peak at 360 Hz in the Fourier transform spectrum was observed. The typical voltage signals and the Fourier transform spectrum in this case are shown in Figs. 11 and 12.

3) When the arc voltage was above 25 V, with less than 10% globular transfer events occurring in a spray mode "background," two predominant peaks at 120 and 360 Hz were observed in the Fourier transform frequency spectrum. The typical voltage signals and the Fourier transform spectrum in this case are shown in Figs. 13 and 14.

4) When over 90% of the transfer events were spray, three predominant peaks were generally observed in the Fourier transform frequency spectrum: 120 Hz, 360 Hz and one in between the first two. Other smaller amplitude peaks may also be present. The typical arc voltage signals and Fourier transform spectrum in this case are shown in Figs. 15 and 16. In this case, even though the 120- and 360-Hz peaks could be confused with the line voltage signals (second harmonics), the second predominant frequency at approximately 190 Hz characterized clearly the spray transfer.

5) When mixed globular, spray and short-circuiting transfer occurred (with less than 3% short-circuiting transfer), only two predominant frequency peaks, at 45 and 360 Hz, can be observed. The typical voltage signals and the Fourier transform spectrum in this case are shown in Figs. 17 and 18.

6) Short-circuiting transfer events involve large fluctuations in arc voltage which tend to predominate the arc signals and affect the outcome of FFT analysis. With over 3% short-circuiting transfer events, the Fourier transform spectrum is uniform, indicating the effect of short-circuiting on masking the effects of other transfer modes. The typical voltage signal and the Fourier transform spectrum in this case are shown in Figs.
Fig. 14 — FFT frequency spectrum of arc voltage signals at the welding condition of 34 V, 74.5 mm/s wire feed rate and 3.8 mm/s travel speed.

Fig. 15 — Welding arc voltage signals at the welding condition of 27 V, 44.5 mm/s wire feed rate and 2.5 mm/s travel speed.

Fig. 16 — FFT frequency spectrum of arc voltage signals at the welding condition of 27 V, 44.5 mm/s wire feed rate and 2.5 mm/s travel speed.

Fig. 17 — Welding arc voltage signals at the welding condition of 27 V, 77.5 mm/s wire feed rate and 4.2 mm/s travel speed.

Fig. 18 — FFT frequency spectrum of arc voltage signals at the welding condition of 27 V, 77.5 mm/s wire feed rate and 4.2 mm/s travel speed.

Fig. 19 — Welding arc voltage signals at the welding condition of 27 V, 63.5 mm/s wire feed rate and 4.2 mm/s travel speed.
As illustrated in the previous paragraphs, the characteristics of the different FFT spectra can be correlated with the different types of metal transfer. When compared with the voltage-time plots and the \( \Delta u \) criteria, characterization of metal transfer mode using FFT is simpler and more conclusive.

Figure 12 is a typical FFT spectrum for globular transfer in FCAW. Because of the formation of larger droplets, the metal vapor pressure on the bottom of a droplet (Ref. 5), the interval between two consecutive globular transfers might be long enough to allow the weld pool to oscillate at its natural frequency. Thus, the contribution of the weld pool in time and frequency domain may become noticeable.

Xiao and den Ouden, and Renwich and Richardson (Refs. 9, 10) indicated that the natural frequencies of the weld pool oscillation were 60 Hz and its harmonic frequencies. Since the welding power source was a three-phase machine, the pool oscillation frequency in this case could be 360 Hz resulting in a predominant peak in the spectrum. The disappearance of 60 and 120 Hz might be due to the collision disturbance between the large droplets and the molten weld pool.

Figure 16 is the FFT spectrum for spray mode. Since the droplet size and mass are too small to disturb the weld pool, the natural pool oscillation frequencies of 120 and 360 Hz become predominant. On the other hand, due to the intensive and regular spray, another predominant and characteristic signal peak appeared between 120 and 360 Hz. This characteristic peak increased with welding current (Fig. 21), which confirmed the general observation that small droplet transfer rate increases with current.

The frequency of the characteristic peak varied from 141 to 300 Hz in the current range of 125 to 260 A, with 198 Hz being the average frequency. Because of the process regularity, the transfer rate could be determined by the number of transfer events and the time. By means of computation using the \( \Delta u \) criteria, the average value was determined to be 182 Hz, which is very close to 198 Hz determined by the FFT method. Therefore, the frequency peak can be used as an indicator of the number of droplets in the predominantly spray transfer mode. In addition, it is clear that the band pass filter is effective in minimizing the 60 Hz signals in the FFT spectra.

Figure 14 shows a mixed mode of globular and spray transfer. As discussed previously, globular mode tends to mask the whole frequency spectrum and to present a peak at 360 Hz. Spray mode, however, tends to exhibit frequency peaks at 120 and 360 Hz, and an additional peak at a frequency between the two other peaks. When both modes are operating, the weakest characteristics peak is generally masked and only the 120 and 360 Hz peaks are recognizable, which also explains why the amplitudes of the 120 and 360 Hz peaks in Figs. 14 and 16 are almost the same.

Figure 18 represents the mixed mode of short-circuiting, spray and globular transfer with only the 360-Hz peak recognizable. Short-circuiting was so predominant that it "uniformized" the whole frequency domain. Additionally, an amplitude peak appeared at 45 Hz. It is suspected that this peak may be related to either explosive transfer or droplet pulsation.

A metal transfer mode map was plotted using the data generated by Fourier transform spectra, as shown in Fig. 22. This map agreed well with the one determined using the \( \Delta u \) criteria, indicating the consensus of both sets of criteria developed (from voltage fluctuation and characteristic FFT frequency components). Based on these two diagrams, an operating window of smooth spray transfer (hatched area) could be determined with great confidence — Fig 23. The proposed processing conditions are confirmed by industrial practice.

Conclusions

According to the results of this inves-
The different metal transfer modes.

droplets that can cause visible arc voltage fluctuations significantly. Thus, small number can affect the arc voltage in transient in gas metal arc welding droplet rate.


