A METHODOLOGY FOR THE STUDY OF METAL TRANSFER MODES IN FLUX CORED ARC WELDING

by

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ABSTRACT

Metal transfer modes in FCAW (flux cored arc welding) were investigated by direct and indirect techniques. Metal droplets transferred across the arc were collected and the corresponding welding arc voltage signals were analyzed. The analysis showed that different metal transfer modes exhibited different arc voltage fluctuations. Different ranges of voltage fluctuations (Δu) were used as criteria to distinguish the different kinds of metal transfer modes. The welding arc voltage signals were processed using Fourier Transform to determine the arc stability and spray droplet transfer frequency. Data from the molten droplets collected were used to test the reliability of the Fourier Transform technique. A map of metal transfer modes was plotted and an optimum welding parameter window was determined for FCAW.
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INTRODUCTION

In modern, large-scale fabrication, such as shipbuilding, automatic arc welding is becoming more popular because of its high efficiency and low cost. One of the arc welding processes of growing importance is flux cored arc welding.

When gas shielded flux cored wire welding was introduced in the United States in the late 1950s, it became an immediate success [1] because the process has some remarkable advantages over the shielded metal arc welding. All position gas shielded flux cored arc welding can generate both high tensile strength and good notch toughness welds, in addition to high productivity. Today, flux cored arc welding can even be applied to underwater welding qualifying the process in many applications. Despite the many advantages of FCAW, the process also has disadvantages. The existence of flux makes the arc more complicated than that of the gas metal arc welding process. The monitoring of the metal droplet transfer across the arc is also more difficult. Many experiments have to be performed to determine the welding parameters that will produce a stable arc and quality weldments. More fundamental understanding of the arc and metal transfer will allow for the development of intelligent welding systems that can control the arc precisely.
Welding arc signals, current and voltage, can be collected and analyzed using different techniques. Fourier Transform is one of these techniques. Based on arc stability and other reference indicators, such as slag detachability, bead morphology, etc., the optimal welding parameters can be determined reliably.

The following section provides some background information on metal transfer modes in gas metal arc, flux cored arc welding, and the Fourier Transform analysis of voltage signals related to those processes.
Metal transfer can be described as the transportation of molten metal droplets, inside or outside the welding arc plasma column, from the tip of the electrode to the weld pool. For flux cored welding electrodes, the molten metal droplets and flux can be transferred together or separately, axially or non-axially, depending on the different welding conditions [2]. Several factors that act on the arc and the molten droplet transfer are listed below:

1. Welding materials composition - base material and electrodes;
2. Welding power source characteristics;
3. Shielding gases;
4. Contact tip-to-work distance;
5. Welding parameters such as current and voltage; and
6. Forces on the molten droplet.

All the factors above act together to determine the size and shape of a molten droplet. With a fixed contact tip-to-work distance, the size of the molten droplet determines the arc gap length. Since the arc voltage which is a function of the arc gap length, the relationship between arc voltage and arc gap length is approximately linear within the range of typical welding voltage values, the size of the molten droplet also influences the arc voltage; smaller droplets
lead to less fluctuation of the arc voltage, stabilizing the arc.

According to the size of the molten droplet and transfer characteristics, metal transfer modes can be defined. Arc voltage fluctuation has also been used as a criterion to distinguish different metal transfer modes[3]. The complete IIW classification of metal transfer modes with examples is reproduced in Table I and schematically illustrated in Figure 1.

Among the transfer modes mentioned in Table I, transfer with the most stable arc is the spray transfer mode, with very small droplets. Many molten droplets, as measured in this research, are smaller than a pixel of the computer monitor screen (below 0.1 mm diameter). The very large number of small droplets results in small arc voltage fluctuations, high deposition rate, and excellent weld bead morphology. Thus, spray is regarded as the optimum metal transfer and is widely accepted in industrial structural fabrication.
Table I. International Institute of Welding Classification of Metal Transfer [3].

<table>
<thead>
<tr>
<th>Designation of Transfer Type</th>
<th>Welding Process (examples)</th>
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<tr>
<td>Free-flight transfer</td>
<td>Low-current GMA</td>
</tr>
<tr>
<td>Globular</td>
<td>CO₂ shielded GMA</td>
</tr>
<tr>
<td>Drop</td>
<td></td>
</tr>
<tr>
<td>Repelled</td>
<td>Intermediate-current GMA</td>
</tr>
<tr>
<td>Spray</td>
<td>Medium-current GMA</td>
</tr>
<tr>
<td>Projected</td>
<td>High-current GMA</td>
</tr>
<tr>
<td>Streaming</td>
<td>SMA (covered electrodes)</td>
</tr>
<tr>
<td>Rotating</td>
<td>Short-circuiting GMA</td>
</tr>
<tr>
<td>Explosive</td>
<td>Welding with filler metal</td>
</tr>
<tr>
<td>Bridging transfer</td>
<td>addition</td>
</tr>
<tr>
<td>Short-circuiting</td>
<td>SAW</td>
</tr>
<tr>
<td>Bridging without interruption</td>
<td>SMA, cored wire, electroslag</td>
</tr>
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Figure 1. Schematic drawing of major metal transfer modes in arc welding [3].
The Effect of Welding Materials on the Metal Transfer

The welding arc is actually one kind of the many electrical discharge phenomena. Once the potential difference applied between an anode and a cathode is high enough to overcome the metal surface work function and the air electrical resistance, an arc is established. Usually, a welding arc is comprised of an anode spot, plasma, an anode drop zone, a cathode drop zone and a cathode spot.

A typical welding arc voltage distribution is illustrated in Figure 2. The arc voltage drop includes anode voltage drop \((V_a)\), plasma voltage drop \((V_p)\), and cathode voltage drop \((V_c)\).

\[
V_{arc} = V_a + V_p + V_c \tag{1}
\]

The major voltage drops observed at the anode and cathode are the result of charge recombination in the anode and cathode zone. Thus, it is expected that different electrodes, i.e. welding material, can affect the arc [4]. The plasma voltage drop is also related to the shielding gas and welding materials.

The three voltage drops determine the energy supplied to a weldment, \(Q\), which is given by [5]:

Figure 2. Typical welding arc voltage distribution [5].
\[ Q = I(V_a + V_{KT} + V_w) \]  \[2\]

where \( V_a \) is the anode voltage drop, \( V_w \) is the cathode voltage drop, \( V_{KT} \) is the plasma voltage drop, and \( I \) is the current.

\( V_w \) is a function of the material being welded. Typically, \( V_a \) is 3 eV, \( V_{KT} \) is 1.2 eV, and \( V_w \) is 4.5 eV. The "thermal energy" from the arc plasma, \( IV_{KT} \), is only a small fraction of the total energy (1 eV is estimated to generate a temperature of approximately 11,000K [5]). Thus, perturbations of a few thousand degrees Kelvin will not affect the total arc energy significantly. The two main components of the arc energy are \( IV_a \) and \( IV_w \), which are functions of the welding anode and cathode. Different materials selected affect the total arc energy input, wire melting rate, metal transfer rate, and the arc stability.

The voltage of the plasma column, \( V_p \), in equation [2] is related to the electric conductivity, thermal conductivity, and stability of the arc column. Generally speaking, the gas shielded flux cored arc plasma consists mainly of cations, anions, electrons, slag particles, metal droplets, etc. For direct current, electrode positive (DCEP), flux cored arc welding, the workpiece is negative, so the electrons in the plasma are from the workpiece electronic emission, shielding gas ionization, and particle collisions. The cations come mainly from the slag and shielding gas; the anions are from
the shielding gas atoms, wire, and slag. Thus different welding materials will result in different electrical conduction in the arc because of the different work function, ionization potential, and different number of charge carriers in the plasma. For a fixed welding condition, better arc electrical conduction requires lower voltage to maintain the arc, provides higher thermal conductivity, and a more stable arc.

The Effect of Welding Power Source

If the welding arc is considered as a dynamic resistance which is a function of arc voltage \( u \) and arc current \( i \), its static voltage-current characteristics [6] can be modeled as shown in Figure 3. Usually, the flat section (region II) is used in SMAW, the rising section (region III) is used in GMAW, FCAW, and other automatic welding processes. If the power source output characteristic curves [6] are superimposed on the static arc curve as shown in Figure 4, the intersection of these curves is the working point set by the user. The degree of fluctuation of this point is an indicator of the ability of the welding power source to provide stable operating parameters; the smaller the fluctuation, the better the power source.
Figure 3. Static voltage-current characteristics of a welding arc [6].
Figure 4. Working point determination based on welding power source output and the static arc characteristic [6].
During welding, the welding arc voltage and current fluctuate with time due to the arc gap length variation as shown in Figure 5. This phenomenon is dynamic because it reflects the capability of the power source at reacting the welding voltage and current to the present instantaneous arc gap. Other indicators such as $\Delta u/\Delta t$ and $\Delta i/\Delta t$ are also used as criteria to evaluate the response of a welding power source.

Since the arc voltage and current are always varying, there will be some good operating ranges, surrounded by arc characteristics curves and machine output characteristics curves, as shadowed in Figure 6, in which arc voltage and current fluctuations are smaller than in other ranges. These boxes are named the operating window or tolerance box, within which, a stable arc can be achieved. Different arc welding processes and welding conditions will result in optimum welding parameters.

Besides controlling the welding parameters to attain a stable arc, new generations of pulsed welding systems have been developed to promote smooth and controlled transfer of the molten droplets. Many of these systems have the capability of real-time arc voltage and current adjustments by means of closed-loop signal feedback and control.
Figure 5. Welding arc voltage fluctuation around the DC arc voltage component at the welding condition of 27 volts, 63.5 mm/s wire feed rate and 3.4 mm/s travel speed.
Figure 6. A region of welding current and voltage because of the welding arc voltage fluctuation [6].
The Effect of Forces on the Molten Droplets

For gas metal shielded arc welding, such as FCAW, the forces which act on the molten droplets are the Lorentz force, gravity force, surface tension, and the gas flow related drag force as shown in Figure 7. Among these forces, the gas drag force causes the axial elongation of the molten droplet toward the weld pool, in a direction opposite to that of surface tension and the gravity force causes elongation of the molten droplets in the gravitational direction. The Lorentz force causes the necking of the molten droplets and is the major force that affects the molten droplet transfer. In addition, within each droplet, liquid metal is stirred violently by the electro-magnetic forces, which increases the instability of the droplet. If the tip of an electrode is assumed to be liquid and deformable, Lancaster suggested [7] that its outline can be modeled as a sinusoidal wave, Figure 8. In favor of this model is the fact that the instability of the electrode tip is related to the curvature of the liquid surface and the axial current.

A proposed model of droplet formation is that at short wavelengths the sinusoidal cylinder and the corresponding droplet are stable. As the drop grows its curvature decreases and the effective wavelength increases until it reaches the critical wavelength, $\lambda_c$, at which:
Figure 7. Schematic drawing of the different forces that act on a droplet.
Figure 8. Assumed sinusoidal geometry of the tip of an electrode. \( \lambda \) is wavelength [7].
\[ X_e = 2\pi R_o / \lambda_e \]  

[3]

$X_e$ is the critical axial displacement, $R_o$ is the radius of an equivalent cylinder [7]. Further growth results in instability and an axial displacement away from the pinched region [7]. The shortcoming of this model is that the dispersion analysis described above is based on the assumption of small displacements, whereas those of the droplet are relatively large.

In conclusion, the geometry of a molten droplet is dependent on the different forces that act on the liquid electrode tip. From a pure force balance, the molten droplet will detach when the surface tension is less than the vectorial sum of the Lorentz force, gravity force, and shielding gas drag force in the transfer direction. The pinch force, i.e. Lorentz force, is dependent on the arc current. Higher current generates a stronger pinch force, smaller molten droplets, and generally a more stable arc.

The Effect of Shielding Gases

For gas shielded flux cored arc welding, the gas atoms or molecules are ionized to become a part of the plasma. Usually, mixtures which include one or more of argon, helium,
carbon dioxide and small amounts of oxygen are used as shielding gas. Different gases have different ionization potentials and thermal conductivities, which results in different plasma characteristics and metal transfer behavior.

Argon is inert and provides high alloy recovery in the weld pool in a variety of welding situations. With its moderate ionization potential, argon allows more difficult arc starting somewhat and unstable arc operation. In addition, a high-argon content shielding gas promotes spray transfer. High deposition rates with improved wire deposition efficiency (low spatter levels) are other characteristics of argon as shielding gas.

Different from argon, helium has a high ionization potential requiring higher potential difference to start and maintain the desirable spray arc welding condition. Helium transfers more heat allowing for faster weld travel speeds and a broader weld penetration pattern. This is particularly important in the welding of metals with high thermal conductivity such as aluminum and copper. Also, helium can promote globular transfer at lower wire current densities [8].

As a reactive gas with low ionization potential, oxygen can improve the welding arc stability and increases weld pool fluidity [8]. With an addition of 1 to 5% by volume in argon, it decreases the metal droplet size in the arc and
increases their transfer rate. Oxygen also promotes cathode attachment, further enhancing arc stability. Additionally, it has a substantial influence on the "transition current" (the arc current level which must be met or exceeded in order to develop spray transfer) in the GMAW or FCAW process. Experiments [8] showed that spray transfer can be achieved over a wider range of operating parameters with increasing oxygen concentration in the shielding gas. Generally, oxygen additions are limited to about 5% to minimize a deterioration effect on both the arc and the mechanical properties of the completed weldment. Another interesting phenomenon occurs, when oxygen is added to argon. In the presence of oxygen, metal transfer and arc stability are perturbed by the boiling of the alloy components in the droplets being transferred. The boiling continues until current is increased to such a level that the partial pressure of oxygen exceeds the critical value to result in the formation of an oxide film that covers the molten droplets and prevents it from boiling.

Another commonly used shielding gas is carbon dioxide. When pure CO₂ shielding is employed, a complex interaction of forces on the molten droplet occurs as a metal droplet is formed at the wire tip. These unbalanced forces cause large, unstable droplets to grow and transfer to the weld pool in a random manner. As a result, an excessive amount of spatter is generated along the weld. To improve metal transfer and
minimize spatter, higher current levels and shorter arc lengths are used in some applications. Since carbon dioxide has a higher thermal conductivity, the plasma is hotter [9]. In such a higher temperature environment, silicon dioxide that is present in the droplets may break down to form silicon monoxide. The flow of this gaseous suboxide forms an insulating film between the droplet and the plasma. Consequently, the partial pressure of oxygen can not reach the critical value to stop the boiling of the alloying elements as discussed before. As a result of metal vapor and gas flow, repelled transfer mode occurs [9].

Argon and carbon dioxide mixtures are also commonly used as shielding gas. With over 20% CO₂ in argon, a short circuiting/globular transfer is observed. The Ar/CO₂ mixtures containing less than 20% CO₂ can produce short circuiting as well as spray transfer [8]. "Tri-mixes" such as Ar-CO₂-O₂, Ar-He-CO₂, Ar-CO₂-H₂ are also available.

Shielding gas selection is a key variable for achieving better welding performance. It is critical to understand how the different shielding gases may influence metal transfer.
The Effect of Contact Tip-to-Work Distance

The contact tip-to-work distance is the summation of electrode extension and arc gap length. Once the voltage is fixed, the arc gap length is also determined. As the electrode extension increases with the distance between the contact tip and the workpiece, the ohmic heating also increases and affects wire melting characteristics and metal transfer. For flux cored electrodes the melting characteristic curve at lower wire feed rates appear rather vertical, compared with the curves at higher feed rates, as shown in Figure 9. This may be due to the influence of the contribution of ohmic heating to the wire melting.

At low current, the ohmic heat generated is low and can be conducted away into the flux. Additionally, the time allowed for heat conduction at lower current (slower wire feed rate) is longer than that allowed at higher wire feed rates. This reduces the influence of ohmic heat on the electrode melting rate. At higher wire feed rates, due to larger current density and shorter heat conduction time, the effect of ohmic heat to electrode melting is more evident. Having the heat concentrated in the metal sheath of the electrode, the electrode extension is more readily to be melted and to be transferred. Consequently, the transfer rate is increased with the size of the droplets reduced [2].
Figure 9. Effect of wire extension on electrode melting rate at high current density [2].
The Effect of Welding Parameters

Current is the most influential factor that affects metal transfer in the low welding current range, or more accurately, in the low current density range. During the study of GMAW metal transfer, Lesnewich [10]-[12] reported a transition current at 250 amperes in carbon steel welding using a solid electrode of 0.045 in. (1.143 mm) diameter with constant arc length and 99%Ar-1%O₂ shielding gas, Figure 10. More recently, Liu [13] also observed a transition current at 200 amperes when voltage was maintained at about 26 volts. On the other hand, Ludwig [14][15] observed no transition current between 200 to 450 amperes. According to Watanabe et al. [16], in high current density welding, using 4.0 mm diameter solid wire, the transition from streaming to globular was continuous with respect to welding current and arc voltage. They covered the current range from 500 to 1000 amperes and the arc voltage range from 20 to 40 volts. This point of view is also implied by Liu et al. [13] because a continuous, mixed globular and spray transfer were observed between the spray, globular, and short-circuiting region Figure 11.

All of the studies above were concerned with the effect of transition current on metal transfer at the low current density range. However, as mentioned by Watanabe et al.
Figure 10. Effect of welding current on droplet transfer rate [3].
Figure 11. Metal transfer mode map for gas metal arc welding [13].
[16], the effect of voltage is progressively more important at the high current density range because the repelling force that acts on the anode spots due to metal vaporization, increases with arc voltage. With a high enough voltage, the repelling force can even stop the metal from transferring into the weld pool. Another important role of welding voltage is that it can also determine the relative percentage of each participating metal transfer mode, as shown in Figure 12. Liu observed no pure metal transfer mode in GMAW (gas metal arc welding) [13]. In most cases, two or three modes coexist. Other parameters, such as travel speed, torch angle, etc., have only minor effects on metal transfer.

Since metal transfer modes can affect arc stability significantly, much effort is devoted to develop methods for arc control. Optimum operating window determination, pulse current power source, voltage feedback signal control are examples of the development. It is important to control the arc in the desired transfer mode, particularly in a fully automatic welding process, so that high quality welds may be produced.
Figure 12. Effect of voltage on the distribution of spray, globular and short-circuiting droplet transfer [13].
The Criteria for Different Transfer Modes
In Gas Metal Arc Welding

Up to now, there have been two kinds of criteria to distinguish different metal transfer modes. These are the voltage fluctuation criterion and the current fluctuation criterion. Liu et al. [13] established the following set of criteria for gas metal arc welding:

- **Noise:** \( \Delta u < 0.5 \) volts
- **Spray:** \( 0.5 < \Delta u < 1 \) volts
- **Globular:** \( 1 < \Delta u < 8 \) volts
- **Short-circuiting:** \( 8 \) volts \( < \Delta u \)

Heald [17], on the other hand, presented a different set of criteria according to the standard deviation of arc current, \( \Delta i \), shown in the following:

1) **Transition from S.C. to spraying:**
   - **Short-circuiting:** \( \Delta i > 20 \) amperes
   - **Transition:** \( 10 < \Delta i < 20 \) amperes
   - **Spray:** \( \Delta i < 10 \) amperes

2) **Transition from globular to spray:**
   - **Spray:** \( \Delta i < 10 \) amperes
   - **Transition:** \( 10 < \Delta i < 20 \) amperes
   - **Globular:** \( \Delta i > 20 \) amperes

Current fluctuation has been suggested as a more reasonable criteria because the current fluctuation amplitude is larger.
than that of the voltage.

**Flux Cored Arc Welding Metal Transfer**

Compared with GMAW and GTAW (gas tungsten arc welding), flux cored arc welding is more complicated because of the flux/metal interaction. During welding, even though the flux and metal sheath are melted together and the droplet detachment frequency of the droplets is very uniform, there is a slight difference in melting rate between the metal sheath and flux. Due to this difference, a small flux pole remains unmelted and protrudes beyond the metal sheath into the arc. However, this flux stick can melt and mix with a molten metal droplet, and be transferred as a single droplet. At higher current and voltage settings (e.g. 380 amperes and 34 volts), the melting rate of the metal sheath becomes much faster than that of the flux, metal droplets were observed to form on one side of the wire tip and transfer non-axially. This results in arc instability [18].

Under the direct current electrode negative (DCEN) condition, the melting rate of the metal stealth is much faster than that of the flux core. As a result, a flux pole extends into the arc column. When the protruding flux pole melts, the flux droplet transfers independently from the metal droplets with little reaction between the molten metal
and flux [18].

The flux not only affects the molten droplet transfer situation, it also affects the droplets size. Matsuda et al. [18] showed that the composition of the flux determines the length of the flux pole. Increasing iron powder in the flux decreased the length of the flux pole and the size of the metal droplets. Even though the addition of iron powder can reduce the droplet size, the amount cannot exceed 40% because of the potential increase of the oxygen and porosities.
EXPERIMENTAL PROCEDURES

Since arc stability is intimately related to the metal transfer mode, a metal transfer modes map, based on the arc voltage and current, is required for process control. The main purpose of this work was to determine the metal droplet transfer frequencies, establish a set of criteria for characterizing different metal transfer modes, map the different metal transfer mode regions for FCAW, and determine the aptness of Fourier Transform as a technique to analyze welding arc signals.

Materials and Equipment

An E71T-1 electrode of diameter 1/16 in. (1.6 mm) was used to produce fillet welds on 6 in. x 4 in. (152.4 x 101.6 mm) A-36 steel coupons. A 75%Ar + 25% CO₂ shielding gas was used. All welds were 94 mm long. The torch angle was set at 45°. The experimental setup is shown schematically in Figure 13. To obtain consistent weldments, a six axis welding robot (PUMA 560) equipped with a Linde VI-450SS constant potential power source were used. A linde DIGIMIG controller was used to control the power supply, gas flow, and integrate the welding process with the robot controller.
Figure 13. Schematic diagram showing the different equipment and setup for molten droplets collection.
Description of the Robot Welding system

The robotic welding system is composed of a robot arm, robot interface controller, welding parameters controller and wire feeder -- DIGIMIG, welding power source, welding torch, shielding gas, and a torch cooler. A Texas Instruments computer is also interfaced with the robotic system for welding program editing and executing.

When a welding program written in VAL language is executed, the robot interface controller receives the program and instructs the robot movements to be performed. The controller also transmits the welding parameters to the DIGIMIG which will control the welding voltage, wire feed rate, and the shielding gas output valve. Thus, the welding open-circuit voltage is established before the robot arm reaches the start position. Once the arm reaches the start position, the welding wire will begin to feed and the shielding gas will flow out of the nozzle. As the arc is ignited, the robot arm moves along the weld path as set in the program.

A simple welding program is included in Appendix 1.
Description of Data Recording System

As shown in Figure 14, the data recording system consists of two voltage dividers, an isolating amplifier, low-pass filter, RTI-820 A/D board, STB-HL02 high-level voltage panel and a Texas Instruments-955 workstation.

The inputs of the recording system are the arc voltage and arc current. The leads to measure the instantaneous arc voltage were prepared by connecting one wire to the torch as a high voltage lead and another one to the base metal as a ground lead. The high voltage lead was connected to a voltage divider in series, which holds a 39:1 voltage ratio and restricts the output voltage to below one volt, as required by the isolating amplifier. Both high voltage and ground leads were connected to channel 1 of the isolating amplifier as the voltage input.

The leads to measure the instantaneous arc current were prepared by connecting two wires in parallel to the shunt inside the welding power source. Then the two leads were connected to channel 2 of the isolating amplifier for arc current input. The isolating amplifier protects the TI workstation and the A/D board from high voltage surges produced by the welding power source. The output of the isolating amplifier becomes the input of the A/D board, with voltage signals connected to channel 0 and current signals to
Figure 14. Schematic diagram showing the data recording system used in the experiments.
channel 1 of the A/D board. An output of 50 millivolts from the shunt is equivalent to 500 amperes of welding current. To avoid the influence of the Nyquist frequency, a low-pass filter was introduced between the isolating amplifier and the A/D board. Based on the A/D board sampling rate and the recording time, a cut-off frequency was set at two KHz. At the end of data sampling, the program also translated the digitized information into real voltage and current, and stored the analog data in two separate files.

The total number of samples of the recorded data for each channel is 6000 points at the sampling rate of about 7.32 KHz for TI-955 workstation. The program used in the data recording is included in Appendix 2.

**Molten Droplets Collection**

To verify the actual number of droplets transferred across the arc and the size distribution of those droplets, a water-cooled copper tube was used as the cathode in a series of "non-melting" welding experiments to collect the molten droplets at the welding condition of 23 volts, 125 in./min (31.8 m/min) wire feed rate (approximately 146 amperes), and 12 in./min (3.0 m/min) travel speed. To achieve better cooling, an aluminum spiral was inserted
inside the copper tube as shown in Figure 15.

When impinged on a cold surface, the droplets solidified and fell into the water below the cathode. The solidified droplets were then collected and processed to remove as much as possible the flux covering the droplets. A stereomicroscope was used to determine the number and size of the droplets. An Image Analysis system was also used to compute the droplets size distribution. Additionally, the welding arc voltage signals recorded were processed by Fast Fourier Transform (FFT) to determine the predominant peaks which corresponded to particular droplet transfer modes in the frequency spectrum. These frequency peaks were then compared with the actual droplets collected to verify the reliability of FFT in determining metal transfer rate.

Fillet Welding Experiments

One hundred and sixty sets of welds were carried out according to the experimental matrix shown in Figure 16. The instantaneous welding arc voltage and current signals were recorded and analyzed by Fourier Transform technique. A computer program was written to calculate the average voltage and current.
Figure 15. The construction of the water cooled copper cathode.
Figure 16. Welding experimental matrix with the travel speed varying from 2.5 to 6.4 mm/s.

Welding Parameter Matrix

Voltage

Wire Feed Rate (in./min)
RESULTS AND DISCUSSIONS

Droplet Transfer Rate

Using a stereomicroscope, the droplets collected were counted and a transfer rate of 2145 droplets per second was found. In order to determine the metal transfer modes, the size distribution (in diameter) of the droplets was computed with an Image Analyzer system. It was observed that most droplets are much smaller than the wire diameter and beyond the resolution of the computer screen pixel, 0.1 mm diameter. From over 40,000 droplets, the image analyzer could only recognize 20% of them. Only a few of the droplets were larger than the wire diameter, indicating clearly that spray was the predominant transfer mode during welding.

The size distribution of the transferred droplets is shown in Figure 17. There are three recognizable peaks in this figure:

Peak1: 0.102 - 0.151 mm, Average: 0.1265 mm;
Peak2: 0.248 - 0.297 mm, Average: 0.2725 mm;
Peak3: 0.394 - 0.443 mm, Average: 0.4185 mm.

Since the size of a droplet affects directly the arc length, fluctuations in arc voltage were also expected from these three typical droplet sizes. In addition, the different
Figure 17. Size distribution of the molten droplets.

Molten Droplets Size Distribution

Diameter (mm)

3000

2000

1000

0

0.102

0.394

0.686

0.978

1.27

# of droplets
size droplets may also experience three different transfer rates, which could affect the stability of the welding arc. To investigate the relationship between the droplet size and the arc voltage fluctuation, Fourier Transform was used to process the welding arc voltage signals which resulted in the amplitude versus frequency diagram shown in Figure 18 and confirmed the presence of three transfer rates at 290, 146 and 95 Hz.

In the frequency domain, the amplitude of a Fourier Transform spectrum indicates the contribution of each individual frequency component to the whole signal. For a welding arc, the amplitude is a function of the signal fluctuation associated with the arc and the number of droplet transfer events. Large arc voltage fluctuations as a result of transferring large droplets will correspond to a high amplitude in the frequency spectrum. On the other hand, the transfer of a large number of droplets, however small the size may be, will also increase the amplitude. This suggests that the three frequencies indicated above, indeed, corresponded to the transfer of droplets of three different sizes. To further correlate the transfer rates with the droplet size, the wire melting rate was measured to be 125 in./min (31.8 m/min) at the actual welding condition mentioned above. Assuming that stable transfer occurred at the rates of 290, 146 and 95 Hz, the total weight of the
Figure 18. FFT frequency spectrum of arc voltage signal at the welding condition of 23 volts, 52.9 mm/s wire feed rate and 5.1 mm/s travel speed.
molten droplets transferred per second can be calculated as the following:

at 290Hz: \[ m_1 = \left( \pi d_{1ave}^3 / 6 \right) \times 7.8 \times 290 = 0.0024 \text{ (grams/s)} \]

at 146Hz: \[ m_2 = \left( \pi d_{2ave}^3 / 6 \right) \times 7.8 \times 146 = 0.0120 \text{ (grams/s)} \]

at 95Hz: \[ m_3 = \left( \pi d_{3ave}^3 / 6 \right) \times 7.8 \times 95 = 0.0284 \text{ (grams/s)} \]

Drops4: \[ m_4 = 0.5060 \text{ (g)} \]

Total: \[ M = m_1 + m_2 + m_3 + m_4 = 0.5496 \text{ (grams/s)} \]

where \( m_1, m_2 \) and \( m_3 \) are the weights of the droplets transferred at 290Hz, 146Hz and 95Hz, respectively. \( d_{1ave}, d_{2ave} \) and \( d_{3ave} \) are the average droplet sizes mentioned previously. Drops4 corresponds to the larger droplets, such as globular and short-circuiting transferred ones. Based on the electrode melting rate, 0.545 grams of metal were melted per second. The extremely small difference between the two masses, i.e., 0.549 grams and 0.545 grams, indicates that 295, 146 and 95 Hz indeed determined the droplet transfer rate at the welding condition of 23 volts, 125 in/min (31.8 m/min) and 12 in/min (3.0 m/min) travel speed. This also shows that the Fourier Transform method can be used reliably to determine the metal transfer rate in welding conditions where spraying mode predominates. Furthermore, it can be concluded that molten droplets, smaller than 0.102 mm in diameter with transfer rate higher than 400 Hz, will not cause significant arc voltage fluctuations in commercial welding power sources.
To distinguish the different metal transfer modes at different welding conditions, a set of criteria based on arc voltage fluctuations is needed.

Since noise is present at all time in a power source, these signals must be eliminated before establishing the criteria. The voltage signal of the power source in open-circuit mode is shown in Figure 19, which showed that voltage fluctuations are smaller than 0.3 volts even at the unusually high setting of 40 volts. For the same reason, voltage fluctuations smaller than 0.3 volts under normal welding conditions used in these experiments are regarded as noise.

In arc voltage-time plots, short-circuiting mode is easy to recognize because of its sharper and deeper arc voltage drop, greater than 10 volts. It seems that spray mode exhibited smaller arc voltage fluctuations, ranging between 0.3 volts to 1 volts. Thus, the criteria can be suggested as the following:

- **Short-circuiting:** \( \Delta u > 10 \) volts;
- **Globular:** \( 1 < \Delta u < 10 \) volts;
- **Spraying:** \( 0.3 < \Delta u < 1 \) volts;
- **Noise:** \( \Delta u < 0.3 \) volts;

After applying this criteria to all the arc voltage signals
Figure 19. Voltage signal of the welding power source at 40 volts in open-circuit mode.
by means of a computer program, listed in Appendix 3, and comparing with arc voltage fluctuations in the arc voltage-time plots, the criteria established seems to behave well. Thus, the criteria is capable of distinguishing different metal transfer modes at different welding conditions. Since the voltage fluctuations caused by spray transfer are small, they can be regarded as background. Once the background is disturbed, the arc is unstable.

FFT Spectrum Characteristics

In signal processing, it is a general rule that if the amplitude of a frequency component is three db higher than that of the neighboring frequency, this component is regarded as a signal. This is known as the "3 db" rule. Db is defined as:

\[ db = 20 \times \log(\text{amplitude}) \]  

To investigate further the relationship between the FFT characteristics and the transfer modes, a "modified 3db" rule was established. Using the C language format, the rule can be stated as:
If (the amplitude of a peak of frequency lower than 400 Hz is 3.5 db higher than that of any other frequency component in a ±50 Hz region)
The amplitude is considered to be predominant and its corresponding frequency component, a signal;
If (the amplitude of a peak of frequency higher than 400 Hz is 3 db higher than that of any other frequency in a ±100 Hz region)
The amplitude is considered to be predominant and its corresponding frequency component, a signal;
else
It is not a signal.
The selection of 3.5 db and 3 db in different frequency range resulted from close examination of the FFT spectra of the FCAW experiments. This rule proved to be capable of separating the signals from the background noise. The computer program that executes the "modified 3 db" rule is listed in Appendix 4.

Using this rule, different frequency spectrum characteristics were correlated with the metal transfer modes determined by the Δu criteria. To avoid low and high frequency noise (below 60 Hz and above 1000 Hz), respectively, attention was focused in the frequency range from 60 Hz to 1000 Hz.

1) When the arc is unstable, with occasional
interruption, because of higher voltage settings, the metal transfer is inconsistent and the Fourier Transform spectrum is uniform with no predominant peaks. This can be recognized easily from the regular voltage ripples shown in a voltage versus time plot. The typical voltage signals and the Fourier Transform plots in this case are shown in Figure 20 and Figure 21.

2) When above 10% globular transfer events occur in a spray background, there is only one predominant peak at 360 Hz in the Fourier Transform spectrum. The typical voltage signal and the Fourier Transform spectrum in this case are shown in Figure 22 and Figure 23.

3) When the arc voltage is above 25 volts, with less than 10% globular transfer occurring in a spray mode background, two predominant peaks at 120 and 360 Hz will exist in the Fourier Transform frequency spectrum. The typical voltage signals and the Fourier Transform plots in this case are shown in Figure 24 and Figure 25.

4) When above 90% spray transfer events happen, there are three predominant peaks at 120, 179 and 360 Hz in Fourier Transform frequency spectrum. Other smaller amplitude peaks are sometimes observed. The typical
Figure 20. Welding arc voltage signal at the welding condition of 36 volts, 40.6 mm/s wire feed rate and 5.1 mm/s travel speed.
Figure 21. FFT frequency spectrum of arc voltage signal at the welding condition of 36 volts, 40.6 mm/s wire feed rate and 5.1 mm/s travel speed.
Figure 22. Welding arc voltage signal at the welding condition of 36 volts, 44.5 mm/s wire feed rate and 5.1 mm/s travel speed.
Figure 23. FFT frequency spectrum of arc voltage signal at the welding condition of 36 volts, 44.5 mm/s wire feed rate and 2.5 mm/s travel speed.
Figure 24. Welding arc voltage signal at the welding condition of 34 volts, 74.5 mm/s wire feed rate and 3.8 mm/s travel speed.
Figure 25. FFT frequency spectrum of arc voltage signal at the welding condition of 34 volts, 74.5 mm/s wire feed rate and 3.8 mm/s travel speed.
arc voltage signals and the Fourier Transform spectrum in this case are shown in Figure 26 and Figure 27.

5) When a mixed mode of globular, spraying and short-circuiting transfer occurs (below 3% short-circuiting transfer), there are two predominant peaks at 120 and 360 Hz respectively. The typical voltage signals and the Fourier Transform spectrum in this case are shown in Figure 28 and Figure 29.

6) When above 3% short-circuiting transfer events happen, the Fourier Transform Spectrum is uniform. The typical voltage signals and the Fourier Transform plots in this case are shown in Figure 30 and Figure 31.

These six cases illustrate that the different metal transfer modes can be effectively distinguished by FFT.

When the arc stops from time to time, the arc voltage fluctuates sharply and largely, like a pulse. The FFT spectrum of a "real" pulse is a horizontal line which covers all frequency components. However, the arc voltage fluctuation caused by arc stop is not a true pulse, reason why the FFT spectrum tends to be uniform. The influence of this voltage fluctuation, compared with that caused by metal transfer, is so predominant that it uniformizes the amplitudes of all individual frequency components. As a
Figure 26. Welding arc voltage signal at the welding condition of 27 volts, 44.5 mm/s wire feed rate and 2.5 mm/s travel speed.
Figure 27. FFT frequency spectrum of arc voltage signal at the welding condition of 27 volts, 44.5 mm/s wire feed rate and 2.5 mm/s travel speed.
Figure 28. Welding arc voltage signal at the welding condition of 27 volts, 77.5 mm/s wire feed rate and 4.2 mm/s travel speed.
Figure 29. FFT frequency spectrum of arc voltage signal at the welding condition of 27 volts, 77.5 mm/s wire feed rate and 4.2 mm/s travel speed.
Figure 30. Welding arc voltage signal at the welding condition of 23 volts, 63.5 mm/s wire feed rate and 4.2 mm/s travel speed.
Figure 31. FFT frequency spectrum of arc voltage signal at the welding condition of 23 volts, 63.5 mm/s wire feed rate and 4.2 mm/s travel speed.
result, it is hard to distinguish which is the predominant frequency. Similarly, the FFT spectrum of the short circuiting mode, with high arc voltage fluctuations also exhibits the uniform amplitude-frequency characteristics.

When a particular number of globular transfer events and/or certain high arc voltage fluctuations happen, the interval between each two consecutive globular transfers might be long enough to allow the weld pool to oscillate at its natural frequency. Then, the arc voltage fluctuation caused by the weld pool oscillation will interfere with the arc voltage fluctuation due to globular transfer. As a result, the FFT frequency spectrum of the weld pool oscillation becomes more noticeable. This can be related to the appearance of the predominant peak at 360 Hz in the FFT frequency spectrum. The effect of weld pool oscillation will be discussed further in the next section.

When the major transfer mode is spray, the size and the mass of the spraying droplets are too small to "disturb" the weld pool oscillation at its natural frequency. The 120 Hz peak, which is a harmonic frequency of 60 Hz and potentially another component of weld pool oscillation frequency, appears in the FFT frequency spectrum besides the 360 Hz. As a result of the predominance and regularity of the spraying transfer events, its signal amplitude in FFT frequency spectrum should be predominant. In fact, the second peak is
observed at a frequency between the 120 and 360 Hz. It is interesting to note that the frequency value of the second peak varied from 141 to 300 Hz in welds with welding current in predominantly spray transfer cases, Figure 32. Increasing welding current increased the spray droplet transfer rate which confirms the general observation that smaller droplets transfer at a higher rate at high current levels.

Comparing the average frequency of the second peak, 198 Hz determined by FFT, with the average number of droplets transferred in the predominant spray transfer cases as determined by the Δu criteria, 182.3 droplets per second, it can be suggested that the second predominant peak in the frequency spectrum can be used as an indicator of the number of droplets transferred in the predominant spray mode, which can cause obvious arc voltage fluctuations.

When a mixture of globular and spray transfer happens, the globular mode tends to uniformize the whole frequency spectrum to only present a peak at 360 Hz. Spray mode, however, tends to dominate the spectrum at the frequencies of 120, 360, and between 120 and 360 Hz. Thus, the weakest amplitude peak in the spray mode FFT spectrum, the frequency component lying between 120 Hz and 360 Hz, is often canceled by the influence of the 360 Hz peak of the globular transfer. When this occurs, only two peaks, at 120 Hz and 360 Hz, are
Figure 32. The variation of the second peak frequency for spray transfer.
present in the frequency spectrum.

For the same reason, when spray, globular and short-circuiting transfer coexist, the number and location of the predominating peaks will depend on the relative percentage of each transfer mode.

**Influence of Weld Pool Oscillation**

To illustrate the influence of weld pool oscillation in the FFT spectrum, the results of welding experiments, with and without a weld pool, are compared.

During "real" welding which was operated at the same welding condition as that of the "non-melting" welding experiment, the weld pool oscillated since it was "disturbed" by the plasma and the electro-magnetic force. The oscillation of the pool causes an oscillation of the arc gap that results in an arc voltage fluctuation. Usually, the oscillation frequency is from 130 to 393 Hz and the corresponding arc voltage fluctuation is about 0.5 volts [19]. Other researchers [20] also reported similar results, indicating that weld pool oscillation frequency lies in the range between 100 and 400 Hz. If a single phase welding power source is used, the pool oscillation frequency is 120
Hz [20]. Thus, it may be deduced that weld pool oscillation is possibly 360 Hz for a three phase power source in the experiment. Weld pool oscillation frequency covers the typical metal transfer rates proved by the "non-melting" experiment discussed previously. Also the weld pool oscillation frequency may cause the arc voltage signal and its FFT spectrum to be different from those in the "non-melting" welding.

Comparing the FFT spectra, shown in Figure 18 and Figure 33, of these two experiments, three recognizable peaks in Figure 33 are located at 129, 179, and 360 Hz, which are quite different from the predominant ones in Figure 18, located at 95, 146, and 290 Hz. Since 120 and 360 Hz are closely related to the weld pool oscillation and their amplitudes are much higher than the same ones in the open-circuit mode, as shown in Figure 34, they may be the frequency components of weld pool oscillation. It shows clearly the influence of weld pool oscillation on the FFT spectrum, and that the weld pool oscillation frequency component(s) tends to be dominating by suppressing the real metal transfer frequency components, at 95 and 290 Hz. The second peak, as the indicator of the transferring rate of the molten droplets which causes an apparent arc voltage fluctuation in the actual welding condition, is still there instead of being covered.
Figure 33. FFT frequency spectrum of arc voltage signal at the welding condition of 23 volts, 52.9 mm/s wire feed rate and 5.1 mm/s travel speed.
Figure 3. FFFT frequency spectrum of the power source voltage signal at 23 volts in open-circuit mode.
Setting the welding parameters to a more spray mode (judged by arc sound), three major peaks were more clearly noticeable in the Fourier Transform spectrum as shown in Figure 35. This indicates that a more stable arc will produce an amplitude-frequency spectrum with more distinguishable peaks at the frequencies discussed above.

Weld pool oscillation not only affects the FFT spectrum, but also might cause the resonance of weld pool, molten droplets, and the network voltage output frequency.

During welding, the plasma covers the weld pool. The stability of the plasma is affected by the gas flow and weld pool significantly. The gas flow is a non-Newtonian flow since the drag force produced by the turbulent flow gas flow sways the plasma continuously. As a result, it may cause a molten droplet to oscillate and the arc voltage to fluctuate in the background. At the same time, the weld pool surface oscillation is driven by the electro-magnetic force. The cathode spot is also in continuous motion. It is this movement that attracts the molten droplet and causes the droplets to oscillate around the axial position resulting in the fluctuation of the arc voltage in the background.

Since weld pool and molten droplet are coupled to oscillate, weld pool oscillation frequency components are significantly affected by the network voltage frequency. Thus, it is quite possible that there is a resonance of the
Figure 35. FFT frequency spectrum of arc voltage signal at the welding condition of 27 volts, 63.5 mm/s wire feed rate and 3.4 mm/s travel speed.
weld pool, molten droplets, and the power source voltage output frequencies. Perhaps, due to this reason, the metal transfer rates seem to relate with the multiple of 60 Hz [21].

**Metal Transfer in FCAW and GMAW**

For a same wire diameter and same welding parameters, the cross sectional area of the metal sheath of a flux cored wire is smaller than that of a solid wire, so the wire melting rate in FCAW is faster than that in GMAW because the actual current density or the heat available to melt the flux cored wire are much higher per unit volume of metal than for that of a solid wire. FCAW actually has no low current density situation. Compared with GMAW metal transfer, no transition current between globular and spray mode, like that in GMAW at about 200 amperes, was observed in FCAW. The reason is that FCAW is a high current density welding process. The lower welding current range of FCAW is equivalent to the higher welding current range in GMAW. In the higher current density ranges, the metal transfer mode change is gradual instead of abrupt, as described in the chapter on metal transfer in arc welding. This agrees with the observations in this FCAW research, and can also explain the existence of a mixture transfer modes in FCAW to be like
a bridge between two transfer modes.

FCAW did not exhibit any pure metal transfer mode during all the welding experiments. Spray transfer is predominant in all the transfer modes like a background. Molten droplets transferred in multiple modes during welding. Different from the "traditional" metal transfer mode concept in GMAW, mixed transfer mode, such as spray and globular transfer, has been reported more frequently by other researchers in recent papers [3], [13], [18], [21].

In predominantly spray mode, for FCAW, because of the existence of the large droplet, the molten slag envelopes the molten metal, the smaller spray droplets have to transfer sideways instead of axially. Also, because of the surface energy difference between the slag and the smaller molten metal droplets, the smaller metal droplet cannot wet the slag. To reduce the free energy, a tiny droplet can be easily produced. For GMAW, the spraying droplet size is determined by the Lorentz force, gravity force, the metal surface tension and the gas dragging force. There is no additional surface energy difference between the slag and the molten metal to reduce the droplet size in GMAW. The size of the spray droplets in FCAW should therefore be smaller than these in GMAW. Besides, to improve the metal deposition rate, much iron powder was added to the flux in the wire used for these experiments. This is another reason why a large number
of droplets transferred in extremely small sizes and caused no arc voltage fluctuations.

In globular and short-circuiting modes, for FCAW, the flux transfers together with the molten metal. The flux holds the molten metal to resist the transfer and accumulate more molten metal, as a result, a large droplet is easy to produce. So the droplet size in FCAW should be larger than in GMAW and as a result, the corresponding arc voltage fluctuations in FCAW are larger than that in GMAW. That is why the $\Delta u$, as the criteria of globular and short-circuiting in FCAW, is larger than for GMAW.

**Metal Transfer Mode Map**

The metal transfer mode map shown in Figure 36 was determined by studying the Fourier Transform frequency spectrum characteristics. On the other hand, percentages of different metal transfer modes in the whole recording time are investigated. The spray mode is predominant in all the situations. When above 10 percent globular transfer events occur, the globular transfer mode influences the whole metal transfer process; and, when above 3 percent short-circuiting transfer events occur, the short-circuiting influences the whole metal transfer process. The influence of globular and
Figure 36. Metal transfer modes determined by FFT.
short-circuiting events, if they occur less than 10 percent and 3 percent, respectively, can be ignored in the whole metal transfer process. Another metal transfer mode map was plotted according to the $\Delta u$ criteria Figure 37. These two maps agree well and can be used to determine the operating parameters for smooth metal transfer and stable arc.
Figure 37. Metal transfer modes determined by $\Delta u$ criteria
CONCLUSIONS

According to the analysis performed in this investigation, the major conclusions are:

1. A large number of molten droplets is typically transferred across the arc in FCAW, approximately, $10^3$ droplets per second. Most of the droplets are smaller than 0.1 mm in diameter.

2. At low current levels (<200 amperes), typical spray transfer rates are around 95, 146 and 290 Hz. Molten droplets transferred at rates higher than 400 Hz do not cause arc voltage fluctuation because of their tiny sizes.

3. Two or more transfer modes coexist at all times.

4. The Fourier Transform is a good technique in determining the different metal transfer situations.

5. The second predominant peak, between 120 and 360 Hz, in a Fourier Transform frequency spectrum can be used as an indicator of the number of droplets transferred in the predominately spray mode. These are the droplets that cause apparent arc voltage fluctuations.

6. A set of $\Delta u$ criteria was established for the determination of FCAW metal transfer modes.
Short-circuiting: \[ \Delta u > 10 \text{ volts} \]
Globular: \[ 1 < \Delta u < 10 \text{ volts} \]
Spray: \[ 0.3 < \Delta u < 1 \text{ volts} \]
Noise: \[ \Delta u < 0.3 \text{ volts} \]

These may be specific to the power supply and electrode used in this investigation.

7. Above 10 percent globular transfer and 3 percent short-circuiting transfer events can affect the arc voltage signal fluctuations significantly. Thus, mixed transfer modes with over 10 percent globular and spray as background can be classified as globular transfer. Mixed modes with over 3 percent short-circuiting can be classified as short-circuiting.
SUGGESTIONS FOR FUTURE WORK

After examining all the arc voltage signals and their Fourier Transform spectra, it seems that globular and short-circuiting transfer can most affect the Fourier Transform frequency spectrum. For example, with spray as the main transfer mode, only a few globular transfers are sufficient to make the second frequency peak between 120 and 360 Hz disappear and confuse the interpretation. The combination of Fourier Transform and ΔU criteria may determine the modes more accurately. Thus, a more in-depth analysis which combines the two concepts needs to be developed.

Another important phenomenon not well explained is that the metal transfer rates are often related to 60 Hz or its multiples. According to the literature, the molten pool oscillation is affected by 60 Hz or its multiples, the same could be true for the molten droplets transfer. There may be a resonance of the network voltage and current, pool oscillation, and molten droplets rates. It is important to analyze the size and mass distribution of the molten droplets to identify their natural frequency to determine the existence of this resonance.

More data is also needed to better characterize the mixed transfer modes.
REFERENCES


APPENDIX 1.

ROBOT WELDING PROGRAM

/***************************************************************/
This program was designed for the robot welding in one of the experiments.

Editor: Wesley Wang

/***************************************************************************/
WELDSET 1 = 125, 23
TOOL ST21
SPEED 20
MOVE #SAFE
WELDSTART 1, 12
DRAW 0,-94,0
WELDEND 0
GAS 2.0
RETRUN

/****************************************************************************** END OF THE PROGRAM ******************************************************************************/
Appendix 2.

DATA RECORDING PROGRAM

This program was designed to record the welding signals data i.e. voltage and current, using RTI-820 A/D board.

Editor: John Steele
Wesley Wang

#include <stdio.h>
#include <conio.h>

#define READINGS 12000

/* the following are global variables */
int count = READINGS;
int array[READINGS], chanarr[3], lchan, board, erstat;
int i;
float volts;
FILE *fpl,*fp2;

main()
{
    double voltage;
    printf ("beginning execution ... initializing \n");
    initialize(&erstat);
    printf("... completed initialization\n");
    if (erstat){
        printf("\n ERROR while initializing RTI, error value %d\n",erstat);
    } else {
        lchan = 1;
        chanarr[0] = 2;
        chanarr[1] = 0;
        chanarr[2] = 1;
        board = 1;
        printf("... calling aing820\n");
        aing820(lchan, board, chanarr, count, &erstat);
        if (erstat) {
            printf("\nAING820 ERROR, error = %d\n",erstat);
        } else {
            printf("... finished AING820(), now we will read values\n");
            aing(lchan, array, &erstat);
            for(i = 0; i < READINGS; i++) {
                printf("array[%d] = %d; ",i,array[i]);
            }
        }
    }
}
if ( !(i % 4) ) printf ("\n" );
} /* end of for loop */
printf("Now we will print the data converted to
voltages");

for(i = 0; i < READINGS; i++) {
    volts = (10.00*array[i])/2047.00;
    printf("voltage[%d] = %f; \n",i,volts);
    if ( !(i % 4) ) printf ("\n" );
} /* end of for loop */

} /* save the volts and current data in different files */
printf("WE ARE NOW GOING TO WRITE TO FILES\n");

if (fpl = fopen("volt.dat","w")) {
    for(i=0;i<READINGS;i += 2)
    {
        volts = (5.00*array[i])/2047.00;
        fprintf(fpl,"%f %f\n",i*(1.0/6400.0),volts);
    }
    close(fpl);
}
else {
    printf("Unable to open Volt.dat\n");
}

fp2 = fopen("current.dat","w");
for(i=1;i<READINGS;i += 2)
{
    volts = (5.00*array[i])/2047.00;
    fprintf(fp2,"%f %f\n",i*(1.0/6400.0),volts);
}

close(fp2);
printf(" The graph data is ready now!\n");
getchar();

END OF THE PROGRAM

**************
APPENDIX 3.

Δu CRITERIA

This program was designed to realize the Δu criteria application

Editor: Wesley Wang
Date: May 1, 1991

#include <stdio.h>
#include <math.h>
main(argc,argv)
int argc;
char *argv[];
{
    float *p,x,peak[2000],vally[2000],du[2000];
    FILE  *in,*out;
    int i,nt,j,s,min,sc,sp,gb,ni,total;
in = fopen(argv[1], "r");
/*out = fopen("p-v.dat", "w");*/
    nt = atoi(argv[2]);
    p = (float*)calloc(nt, sizeof(float));
    rewind(in);
    for(i=0; i<nt; i++)
    {
        fscanf(in, "%f %f \n", &x, p);
        p[i+1] =(*p);
    }
    for (i=1; i<nt; i++)
    {
        if(p[i]>p[i-1])
        {
            if(p[i]>=p[i+1])
            {
                peak[j] = p[i];
                j = j + 1;
            }
            else
            ;
        }
        else
        {
            if(p[i]<p[i+1])
            {
                vally[s] = p[i];
                s = s + 1;
            }
        }
    }
printf("The total number of vallys is %d\n",s-1);
printf("The total number of peaks is %d\n",j-1);

ni = 0;
sp = 0;
gb = 0;
sc = 0;
for (i=0;i<j;i++)
{
    du[i] = (peak[i]-vally[i]);
    if (du[i]<10.0)
    {
        if(du[i]>1.0)
            gb = gb + 1;
        else{
            if(du[i]>0.3)
                sp = sp + 1;
            else{
                ni = ni + 1;
            }
        }
    }
    else
        sc = sc + 1;
}
total = sc + sp + gb + ni;
printf("The # of spray is %f\n", (sp*1.0)/0.64);
printf("The # of G.B. is %f\n", (gb*1.0)/0.64);
printf("The # of S.C. is %f\n", (sc*1.0)/0.64);
printf("The spray percent is %f\n", (sp*100.0)/(total*1.0));
printf("The globule percent is %f\n", (gb*100.0)/(total*1.0));
printf("The short-circuiting percent is %f\n", (sc*100.0)/(total*1.0));
APPENDIX 4.

MODIFIED 3DB RULE

This program was designed to realize the modified 3 db

Editor : Wesley Wang
Date : Dec. 26, 1990

input:     data file;                         output:   predominant peak frequencies value;
**********************************************************
#include <stdio.h>
#include <math.h>
/************* The main program ***********/
main(argc ,  argv
int argc;
char *argv[ ];
{
  FILE *in;
  int i,j,k,h,nt,x,y;
  float *amp,*result,*freq;
  float comp;
  if (argc < 2 )
  {
    fprintf(stderr,
      "usage: (datafile) (items read in the file) \n"
    );
    exit(1);
  }
  if ( (in =fopen(argv[1], "r") )==NULL)
  {
    fprintf(stderr, "I Couldn't open the file "%s". \n",
      argv[1]);
    exit(2);
  }
  //**** allocate pointers for input and output data ****/
  nt = atoi(argv[2]);
  amp = (float*)calloc(nt, sizeof(float));
  result = (float*)calloc(10, sizeof(float));
  freq = (float*)calloc(nt, sizeof(float));
  rewind(in);
  for (i =0 ; i < nt ; i++)
  {
    fscanf(in , " %f %f \n", freq, amp);
    amp[i] = *amp;
    freq[i] = *freq;
  }
h = 0;

for(i=0; i<61; i++)
{
    amp[i] = 0;
}
/**************************** Comparision ***********************/

for(i=60; i<nt; i++)
{
    comp = 105;
    if(freq[i]<400)
    {
        for(j=i-27; j<i; j++)
        {
            if (comp>3.5)
            {
                comp = amp[i] - amp[j];
            }
            else{
                break;
            }
        }
        if(comp>3.5)
        {
            for(j=i+1; j<i+32; j++)
            {
                comp = amp[i] - amp[j];
                if(comp >3.5 )
                {
                    result[h] = freq[i];
                }
                else{
                    break;
                }
            }
            if(comp>3.5)
            {
                h = h + 1;
            }
        }
    }
    if(freq[i]>400)
    {
        for(j =i-99; j<i; j++)
        {
            if(comp>3.0)
            {
                comp = amp[i] - amp[j];
            }
            else{
                break;
            }
        }
    }
if (comp > 3.0)
{
  for (j = i + 1; j < i + 99; j++)
  {
    comp = amp[i] - amp[j];
    if (comp > 3.0)
    {
      result[h] = freq[i];
    } else {
      break;
    }
  }
  if (comp > 3.0)
    h = h + 1;
}

printf("The transferring frequencies are the following:
");
for (i = 0; i < h; i++)
{
  if (result[i] < 1500)
  printf("%f\n", result[i]);
}

(sc*100.0)/(total*1.0));
printf("The noise percent is %f\n", (ni*100.0)/(total*1.0));
printf("The ratio of SP and G.B is %f\n", (sp*1.0)/(gb*1.0));
printf("The ratio of SP and S.C. is %f
", (sp*1.0)/(sc*1.0));
printf("The ratio of G.B. and S.C. is %f\n", (gb*1.0)/(sc*1.0));
close (in);
APPENDIX 5.

FFT PROGRAM

*******************************************************************************
Program of
Fourier Transform, Filter and Spectrum

Editor : Wesley Wang
Data : Dec. 26, 1990
*******************************************************************************

This program is supposed to process the welding arc signal,
i.e. welding voltage and welding current, by means of Fourier
Transform forward and backward as a filter.
input: data file;
output: row data spectrum data file;
        filtered data spectrum data file;
        filtered voltage versus time plot data file.
*******************************************************************************

#include <math.h>
define SWAP(a, b) tempr = (a); (a) = (b); (b) = tempr
define PI 4.0*atan(1.0)

/******* The main program *******

main(argc, argv)
int argc;
char *argv[];
{
FILE *in, *out1, *out2, *out3;
   int i, nt, fq;
float *p, *q, *f, x; /* pointers to input and output data */
float temp, dt;
void realft();

if (argc < 4)
{
fprintf(stderr,
"usage: (datafile) (items read in the file) \n") ;
exit(1);
}
if (! (in = fopen(argv[1], "r") ) == NULL)
{
fprintf(stderr, "I Couldn’t open the file \"%s\". \n", argv[1]);
exit(2);
}

/***** allocate pointers for input and output data *****
nt = atoi(argv[2]);
dt = atof(argv[3]);
p = (float*)calloc(nt, sizeof(float));
q = (float*)calloc(nt, sizeof(float));
f = (float*)calloc(nt, sizeof(float));
rewind(in);
for (i =0 ; i < nt ; i++)
{
  fscanf(in , " %f %f \n",&x, p);
  if (i == 0 ) temp = p[i] ;
  p[i] = *p;
}
p[0] = temp ;
/**************** Call FFT program *****************/
realft(p-1 , nt/2, 1);
for(i=2;  i<nt; i+=2) /* row data spectrums */
{
  q[i/2] = 2.0 * (p[i]*p[i] +p[i+1]*p[i+1]);
}
q[nt/2] = 2*p[1]*p[1];
q[0] = 2*p[0]*p[0];
outl = fopen("fowfft.dat", "w");
for(i=0; i<=nt/2; i++)
{
  q[i] = 20*log10((double)q[i]);
  f[i] = i/(nt*dt);
  fprintf(outl, "%f %f
", f[i], q[i]);
}
for(i=0; i<(int)(60*nt*dt); i++) /* as a filter */
{
  p[i] = 0;
}
for(i=(int)(1000*nt*dt); i<nt; i++)
{
  p[i] = 0;
}
for(i=2; i<nt; i+=2)
{
  q[i/2] = 2.0*(p[i]*p[i]+p[i+1]*p[i+1]);
}
q[nt/2] = 2*p[1]*p[1];
q[0] = 2*p[0]*p[0];
out2 = fopen("filter.dat","w"); /* filtered spectrum */
for(i=0; i<=nt/2; i++)
{
  q[i] = 20*log10((double)q[i]);
\[ f[i] = \frac{i}{(nt \cdot dt)}; \]
\[
\text{fprintf(out2, "\%f \%f\n", f[i], q[i]);}
\]
\[
\text{realft(p-1, nt/2, -1); /* filtered v-t dat */}
\]
\[
\text{out3 = fopen("bakfft.dat","w");}
\]
\[
\text{for(i=0; i<nt; i++)}
\]
\[
\text{fprintf(out3, "\%f \%f\n", (1.0*i)*dt*2*p[i]/nt);}
\]
\[
\text{fclose(in);} \]
\[
\text{fclose(out1);} \]
\[
\text{fclose(out2);} \]
\[
\text{fclose(out3);} \]
\[
\text{/* free workspace */}
\]
\[
\text{free(p);} \]
\[
\text{free(q);} \]
\[
\text{free(f);} \]
\[
\text{/* End of Main Program */}
\]
\[
\text{// Calculates the Fourier transform of a set of 2n real valued}
\]
\[
\text{data points}
\]
\[
\text{// double precision for the trigonometric}
\]
\[
\text{void realft(data, n, isign)}
\]
\[
\text{float data[];}
\]
\[
\text{int n, isign;}
\]
\[
\text{int i,il , i2, i3, i4, n2p3;}
\]
\[
\text{float c1 = 0.5, c2, hlr, hli, h2r, h2i;}
\]
\[
\text{double wr, wi, wpr, wpi, wtemp, theta;}
\]
\[
\text{/* double precision for the trigonometric}
\]
\[
\text{recurrences. */}
\]
\[
\text{void fourl( );}
\]
\[
\text{theta = \pi/(double)n; /* initialize the recurrence. */}
\]
\[
\text{if ( isign == 1) {}
\]
\[
\text{c2 = -0.5;}
\]
\[
\text{fourl(data, n , 1); /* the forward}
\]
\[
\text{transform is here. */}
\]
\[
\text{else{}
\]
\[
\text{c2 = 0.5;}
\]
\[
\text{theta = -theta;}
\]
\[
\text{}}}
\]
\[
\text{wtemp = sin(0.5*theta);}
\]
\[
\text{wpr = -2.0*wtemp*wtemp;}
\]
\[
\text{wpi = sin(theta);}
\]
\[
\text{wr = 1.0 + wpr;}
\]
\[
\text{wi = wpi;}
\]
n2p3 = 2*n + 3;
for (i = 2; i<=n/2; i++) {
    i4 = 1+(i3=n2p3-(i2=1+(i1=i+i-1)));
    hlr = c1*(data[i1] + data[i3]);
    /* The two separate transforms are separated out of data */
    hli = c1*(data[i2] - data[i4]);
    h2r = -c2*(data[i2] + data[i4]);
    h2i = c2*(data[i1] - data[i3]);
    /*Here they ar recombined to form the true trasform of the
    original real data.*/
    data[i1] = hlr + wr*h2r - wi*h2i;
    data[i2] = hli + wr*h2i + wi*h2r;
    data[i3] = hlr - wr*h2r + wi*h2i;
    data[i4] = -hli + wr*h2i + wi*h2r;
    wr = (wtemp = wr)*wpr-wi*wpi + wr;
    /*************** The recurrence *******************/
    wi = wi*wpr + wtemp*wpi + wi;
}
if (isign == 1) {
    /*Squeeze the first and last data together to get them all
    within the original array */
    data[1] = (hlr = data[1]) +data[2];
} else {
    data[1] = c1*((hlr = data[1]) + data[2]);
    fourl(data, n, -1);
    /********** This is the inverse transform ***********/
}

/********** The discrete fourier transform ***********/
void fourl(data, nn, isign)
float data[ ];
int nn, isign;
{
    int n, mmax, m, j, istep, i;
    double wtemp, wr, wpr, wpi, wi, theta;
    /* double precision for the
    trigonometric recurrences.*/
    float tempr, tempi;
    n =nn <<1;
    j = 1;
    for(i = 1; i < n; i += 2) {
        /* this is the bit-reversal section of
        the routine. */
        if (j>1){
            /********** Exchange the two complex numbers.***********/
            SWAP(data[j], data[i]);
            }
SWAP(data[j + 1], data[i + 1]);
}
m = n >> 1;
while (m >= 2 && j > m) {
j -= m;
m >>= 1;
}
j += m;
*/

/* here begins the Danieison-Lanczos section of the routine */
out loop executed log2 nn times. */
mmax = 2;
while (n > mmax) {
    istep = 2*mmax;
    theta = 2.0*PI*isign/(double)(mmax);
    /**** Initialize for the trigonometric recurrence. ****/
    wtemp = sin(0.5*theta);
    wpr = -2.0*wtemp*wtemp;
    wpi = sin(theta);
    wr = 1.0;
    wi = 0.0;
    for(m=1; m<mmax; m+=2){
        /*********** Here are two nested inner loops. ***********/
        for (i = m; i <= n; i += istep) {
            j = i + mmax;
            /***** This is the Danieison-Lanczos formula: *******/
            tempr = wr*data[j] - wi*data[j+1];
            tempi = wr*data[j+1] + wi*data[j];
            data[j] = data[i] - tempr;
            data[j+1] = data[i+1] - tempi;
            data[i] += tempr;
            data[i+1] += tempi;
        }
    /*************** Trigonometric recurrence. *************/
    wr = (wtemp = wr)*wpr - wi*wpi+wr;
    wi = wi*wpr + wtemp*wpi + wi;
    }mmax = istep;
}