Metal Transfer in Gas Metal Arc Welding: Droplet Rate

A study of droplet rates for various transfer modes verifies optimum operating parameters

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ABSTRACT. This study reports the changes in droplet-transfer mode and rate during gas metal arc welding as the voltage is varied at a series of current levels. The droplet-transfer rate was found to be maximum (approximately 100 s^{-1}) for the voltage/current combinations that are normally suggested by the electrode manufacturers and are considered optimum in the judgment of experienced welders. At voltages above or below the 1-V-wide optimum range, the transfer rate decreased by about 10 s^{-1} per V in the vicinity of the optimum condition. Furthermore, statistical analysis of the arc current and voltage data showed that during operation outside the optimum range, the welding arc was unstable and the current output was very irregular with varying cycle time between each droplet transfer. At the maximum droplet-transfer rate, the droplet-transfer cycle time was very consistent and revealed a narrow rate range, which correlated with the high stability and lower spatter at these optimum operating conditions. The possibility of using the concept of maximum droplet-transfer rate range with minimum rate fluctuation and corresponding arc current-voltage signals as a means of short-circuiting welding process control and automation is being considered. At voltages below the optimum range, high-speed video recording confirmed that the short-circuiting transfer was very unstable and the arc reignited explosively. Above the optimum voltage, the arc became longer and the droplets became visibly larger, with mixed globular and short-circuiting transfer. The droplets, however, were no longer directed uniformly to the weld pool, resulting in increased spatter.

Introduction

Metal Transfer Mode in Arc Welding

Arc welding includes the major joining processes used in manufacturing industries. Examples are shielded metal arc (SMA), gas metal arc (GMA), flux cored arc (FCA), submerged arc (SA) and gas tungsten arc (GTA) welding. With the exception of GTA welding, all these processes require a consumable electrode, which has the dual function of carrying the current that heats the weld pool and providing filler metal to complete the weld joint. This dual function has long been a topic of research. Spraragen and Lengyel (Ref. 1) reviewed the basic principles of an electric arc and summarized the development of the field of welding arc physics. In particular, they concluded that in the area of liquid metal transfer from the electrode to the weld pool, the electromagnetic pinch force, gravity, shielding gas drag force and surface tension are the major forces that act on the electrode tip. Using high-speed cinematographic techniques, Muller, Greene, and Rothschild (Ref. 2) found that large spherical liquid-metal droplets in a GMA arc decreased in size with increasing current. As the electrode feed rate was continuously increased, however, a sudden decrease in droplet size occurred at what was termed the transition current. In addition, they determined that with inert gas shielding, the droplet composition remained constant during the metal transfer.

Lesnewich (Refs. 3–5) investigated the physics of arc welding using SMA and GMA welding. Particularly, he studied the effects of welding process parameters such as current, voltage, electrode polarity, electrode extension and diameter on the electrode melting rate and metal transfer. In carbon steel welding of 1.2-mm (0.045-in.) diameter electrodes with constant arc length and 99% Ar-1% O_2 shielding gas, a transition in metal transfer occurred at approximately 250 A, and below this current, the droplet rate decreased abruptly from more than 200 to 10 s^{-1}. Figure 1 illustrates this transition in droplet-transfer rate with welding current. The transition current increased with increasing electrode diameter and decreased with increasing electrode extension.

From his GMAW studies, Ludwig (Refs. 6, 7) confirmed that the electromagnetic force is the major force among the chemical and physical forces that affect the formation and subsequent transfer of metal droplets. Over a welding current range of 200 to 450 A, no abrupt change in metal transfer was observed. The frequency of droplet transfer decreased continuously with decreasing welding current, as shown in Fig. 1. Pintard (Ref. 8) also observed no abrupt variation in the transfer rate at current levels below 220 A. However, there was a transfer mode change at 190 A. Above this current level, the electrode tip shape changed from hemispherical to conical, and the metal droplets, which detached from the tip of the electrode became smaller than the electrode diameter.

Needham, Cooksey and Milner (Ref. 9) investigated the droplet-transfer rate for aluminum GMAW and confirmed the presence of a transition current. Disconti-

KEY WORDS

Droplet Transfer t_D
GMAW Metal Transfer
Droplet Rate
Droplet-Transfer Mode
Short Circuiting
Globular Transfer
Statistical Analysis
Current Variations
Voltage Variations
Arc Behavior

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nuity in the droplet rate was seen at the transition current. In a more recent investigation of aluminum-magnesium alloys welding, Woods (Ref. 10) showed the importance of the electrode chemical composition in determining the metal transfer mode and spatter levels. He indicated that the transfer characteristics of all alloy filler metal electrodes would also depend upon the concentration of the high-vapor-pressure alloying elements incorporated in the electrodes. Vaporization of elements such as magnesium and zinc could cause arc instability and in-flight explosion of the metal droplets, resulting in unstable metal transfer.

One of the most up-to-date and comprehensive reviews of metal transfer modes during arc welding was written by Lancaster (Ref. 11). According to the IIW nomenclature referenced in his book (Ref. 12), metal transfer can be classified into three main groups: free-flight transfer, bridging transfer and slag-protected transfer. In free-flight transfer, the electrode does not contact the molten metal pool. Metal droplets detach from the tip of the electrode and move across the arc column. When the electrode contacts the weld pool, bridging transfer occurs. For welding processes that use large amounts of fluxes, metal transfer may involve layers of slag, known as slag-protected transfer. The complete IIW classification of metal transfer modes with examples is reproduced in Table 1 and schematically illustrated in Fig. 2.

In most of the welding literature, the metal transfer mode is described only by the terms of short-circuiting, globular and spray. At low-current and low-voltage levels, short-circuiting transfer (intermittent-bridging transfer) occurs. At a slightly higher voltage level, globular (free-flight) transfer results. And above the transition current, fine metal droplets are propelled across the arc towards the weld pool and spray (free-flight) transfer becomes the predominant mechanism.

Short-Circuiting Transfer in CO_2 Welding

In the early 1950's, carbon dioxide (CO_2) was introduced in Europe as an alternate shielding gas in arc welding. Aside from the high welding speed and deposition rate, and good weld penetration achieved in CO_2 welding, the main reason for utilizing this reactive gas is its low cost. However, the improper use of CO_2 causes a large amount of spatter, which may clog the gas ports of a welding gun and allow nitrogen to enter the weld pool and embrittle it. Furthermore, postweld cleaning and grinding operations are often required to remove the spatter. Therefore, several researchers have tried to develop a better understanding of the metal transfer characteristics of this process for better use of this

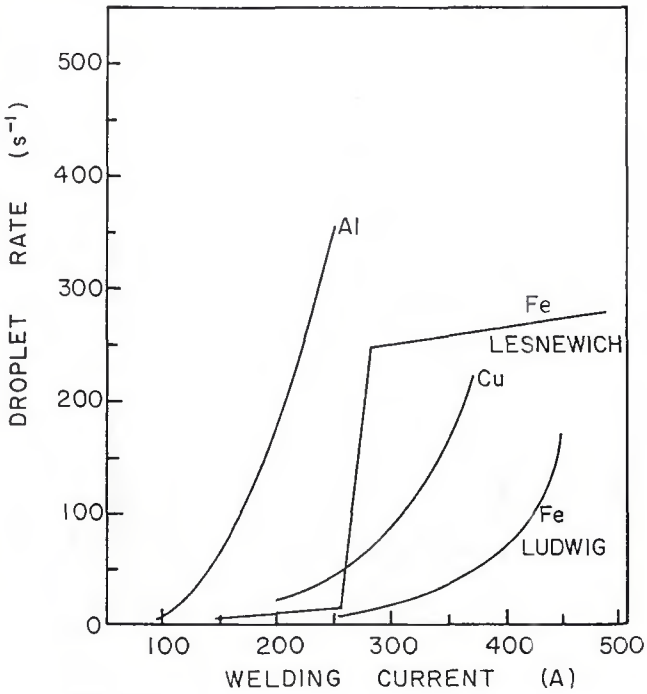

Fig. 1—Transition in droplet-transfer rate as a function of welding current

economical shielding gas (Refs. 13–15).

In CO_2 welding, Dilthey (Ref. 16) reported three modes of metal transfer: globular, subarc and short-circuiting. During globular transfer, large metal drops are formed. Some of these droplets are repelled from the electrode tip; they move upward or sideways in an irregular pattern, and deposit outside the molten pool in the form of spatter. The subarc mode is characterized by a higher current density; the arc has a very short length (low voltage) and occurs below the workpiece surface. Small droplets are detached and transferred across the arc. According to Rothschild (Ref. 17), subarc cannot be classified as a true spray transfer since the droplets are transferred laterally into the weld pool.

In the short-circuiting mode, the electrode feed rate is slightly higher than the melting rate in the arcing mode, so the tip of the electrode eventually dips into the molten pool and extinguishes the arc (Ref. 18). This short circuit reduces the arc voltage to zero and causes the welding current to rise very rapidly. During this period of increased current flow, the electrode heats according to Joule's law and begins to melt. The electromagnetic pinch force also increases strongly, pushing the molten metal in the electrode

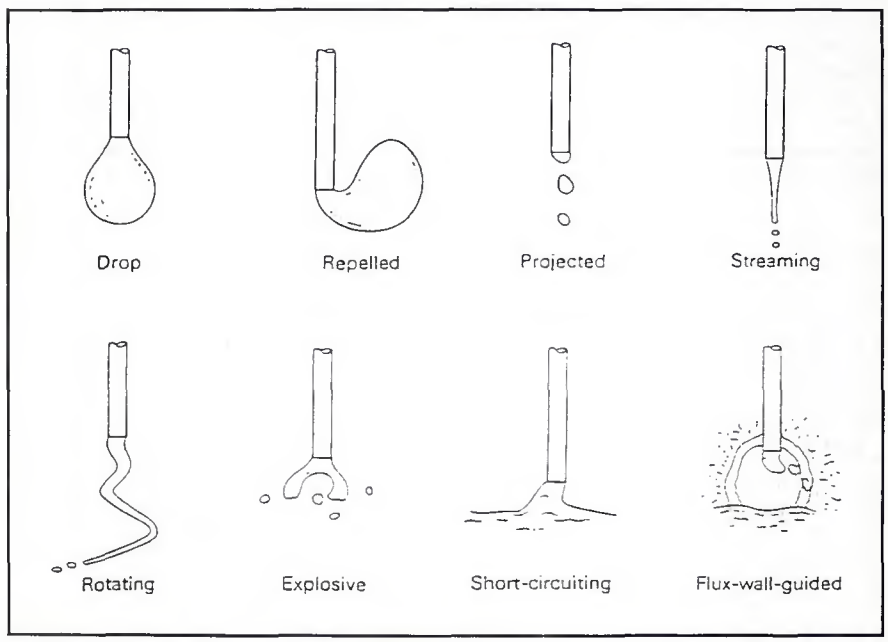

Fig. 2—Metal transfer modes in arc welding

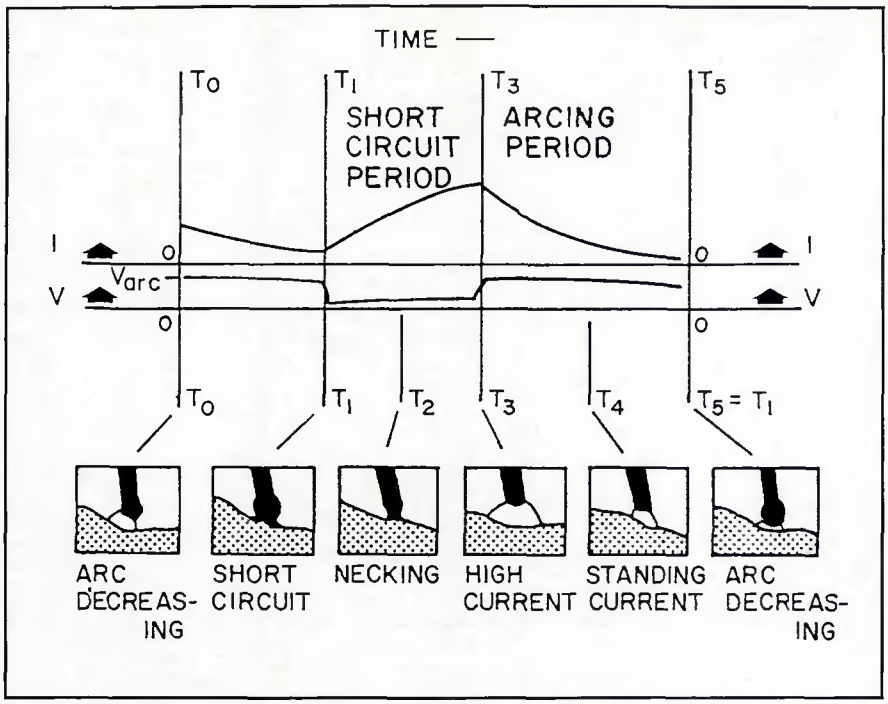

Fig. 3—Instantaneous arc current and voltage variation during short-circuiting transfer

towards the workpiece. As the liquid metal flows under the influence of the pinch force, a neck begins to develop near the solid-liquid interface at the tip of the electrode. Surface tension also plays an important role in the necking of the electrode tip. Finally, the neck breaks and the droplet is transferred. At this point, the arc is reignited, and the voltage reaches its peak value while the current decreases. The tip of the electrode adjacent to the arc continues to melt as it moves toward the molten pool. This process repeats at approximately 20 to 200 s^{-1}. The current and voltage characteristics of the arc can be monitored and recorded with a high-speed oscilloscope. Figure 3 illustrates the current and voltage record during short-circuiting welding.

In most applications, a stable arc with uniform transfer is required to obtain a spatter-free weld with the proper bead morphology. For thin-plate welding, process stability and quality weldments are extremely dependent on the careful adjustment of the welding parameters. The increase in current and rate of increase during the short circuiting of the electrode with the molten metal pool are extremely important in promoting stability. The current must increase rapidly at first to create sufficient electromagnetic pinch force for drop detachment, but the maximum current must be limited so that the electromagnetic forces do not cause excessive spatter (Ref. 18).

Kolasa, Matsunawa and Arata (Ref. 19) investigated the effects of welding current and voltage on short-circuiting rate in CO_2 welding and determined that the dynamic characteristics of a power supply can significantly affect the process stability. In many aspects, the results from Kolasa's work confirmed previous findings of other researchers (Refs. 13–15, 20, 21). However, short circuiting was observed at up to 300 A without the abrupt transition reported by Lesnewich (Ref. 5). Rather, they observed a wide range of short-circuiting frequencies, from approximately 10 to 100 Hz, for different current and voltage settings. Lucas (Ref. 22) studied the effects of shielding gas, chemical composition of welding consumables, type of power source and contact-tip internal diameter on the process stability of short-circuiting welding. He used the standard deviation of the peak current measurements as the indicator of the stability and uniformity of the process. For a particular current level, the voltage that provides a minimum standard deviation in peak current was correlated with the optimum welding potential, as determined empirically during welding.

Our study investigates the combined effects of current and voltage on short-circuiting transfer of low-carbon steels during welding with CO_2 and Ar-O_2 shielding gases. In particular, parameter selection via empirical methods, such as smooth arc and uniform arc noise, is explained in terms of basic arc phenomena, such as the current and voltage relationship and the metal-transfer characteristics. The results of metal transfer determined in the present study are compared with that reported in the literature.

Broadly speaking, computer-generated data that can reach the same conclusions as an experienced welding operator permits substantial automation and brings its benefits to welding. In the manufacturing world of today, automation and quality assurance are the leading factors of success. Hence, the concept of using maximum droplet-transfer-rate range with minimum rate fluctuation as proposed for study in this paper, and using the corresponding arc current-voltage signals as a means of short-circuiting welding process control and automation were the driving forces for conducting this research.

Table 1—International Institute of Welding Classifications of Metal Transfer

	Designation of Transfer Type	Welding Process (examples)
1.	Free-flight transfer	
1.1	Globular	
1.1.1	Drop	Low-current GMA
1.1.2	Repelled	CO_2 shielded GMA
1.2	Spray	
1.2.1	Projected	Intermediate-current GMA
1.2.2	Streaming	Medium-current GMA
1.2.3	Rotating	High-current GMA
1.3	Explosive	SMA (covered electrodes)
2.	Bridging transfer	
2.1	Short-circuiting	Short-circuiting GMA
2.2	Bridging without interruption	Welding with filler metal addition
3.	Slag-protected transfer	
3.1	Flux-wall guided	SAW
3.2	Other modes	SMA, cored wire, electroslag

Experimental Procedure

Bead-on-plate welds were prepared on ASTM Type A36 steel using 100% CO_2 as the shielding gas. A 1.2-mm (0.045-in.) diameter ER70S-3 electrode was used. Welding parameters were varied from 125 to 225 A and 20 to 29 V. A transistorized current regulator with variable slope control was used to simulate a constant-potential power source and to set the operating parameters precisely. Unlike most power supplies, the

transistorized current regulator had a voltage ripple that was less than 0.1 V.

At each combination of current and voltage, the welding arc and droplet transfer were recorded by a high-speed video system with the capability of instant frame-by-frame replay. The video system was capable of filming 300 frames per s, which was adequate for resolving individual droplet transfer in the short-circuiting mode. Arc observation and recording were enhanced by a laser backlighting setup as shown in Fig. 4. A series of optical filters introduced in the laser beam path reduced interference from the arc light.

Arc current and voltage variations were captured on a digital high-speed oscilloscope. In addition to real-time evaluation, the instantaneous values of current and voltage were stored on diskettes for later retrieval and analysis. After the welds were completed, the surface appearance, wetting, ripple pattern and convexity of the beads were also examined.

A second set of welds was made using 98% Ar-2% O_2 shielding. The same range of parameters as those of CO_2 welds was used and the weld evaluation followed the procedure described above.

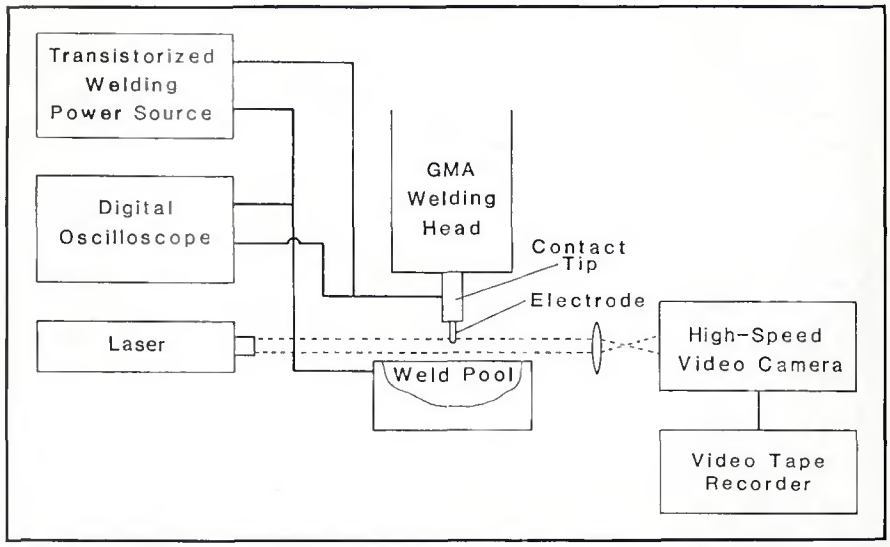

Fig. 4—Schematic of the experimental equipment

Table 2—Summary of Some Statistical Predictors for the Characterization of the Time between Transfers (t_D) in Milliseconds for the 150-A Welds

Volts	Mean t_D	Standard Deviation of t_D	Standard Error of Mean t_D	Maximum t_D	Minimum t_D
20.4	24.3	22.6	3.2	95.8	6.6
21.0	9.6	1.7	0.2	13.0	5.6
22.4	12.7	2.5	0.4	17.8	6.6
24.4	12.3	3.4	0.5	18.2	3.2
26.4	13.4	6.7	0.9	29.6	3.4

Results and Discussion

Statistical Analysis of the Current and Voltage Variations

Figure 3 shows that the period of a complete short-circuiting transfer cycle may be divided into four subperiods: short circuiting, rapid rise in voltage as the arc ignites, arcing and rapid drop in voltage as the arc extinguishes. The duration of each subperiod can be easily determined from a current-time or voltage-time plot. Correspondence between the arc periods and electrical signals is confirmed by the high-speed video record. In this study, the peak current and voltage values did not vary significantly and the transfer-cycle shapes remained fairly uniform. Therefore, the performance of the welding process can be described by the statistical variation in the period of the transfer cycle (the time between two consecutive droplet transfers) or droplet rate. For a given electrode feed, a long period means a long time for melting and droplet growth. This causes a larger droplet size and increases the splash and spatter in a weld pool. Furthermore, chemical reactions may cause gas evolution in the droplet, which may lead to in-flight explosions and spatter. The long period of stable arcing could also indicate the proximity of a transition to the lower frequency globular-transfer mode.

The instantaneous welding current and potential as a function of time were analyzed statistically to determine the time needed for successive droplet transfers (t_D). Figure 5 shows typical arc current and voltage curves, from which the time between successive short circuits and the average short-circuiting rate were determined. Of the many different statistical parameters examined, the mean, standard deviation, standard error of the mean and the maximum and minimum of transfer periods characterize the transfer best. A summary of the statistical analysis of the t_D data for the 150-A welds is given in Table 2. Figures 6–8 illustrate the variation of the mean, standard deviation, and standard error of the mean for the t_D data as function of voltage. For welds prepared at 150 A, the mean t_D reaches a minimum of 9.56 ms at 21 V. At this particular current-voltage combination, the standard deviation and standard error of the mean t_D were also minimized, indicating that the t_D popula-

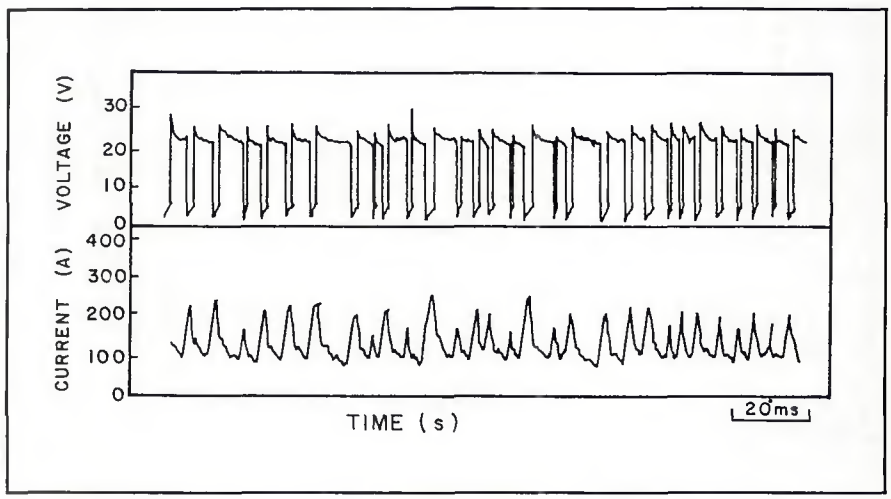

Fig. 5—Typical arc current and voltage variation recorded by high-speed digital oscilloscope

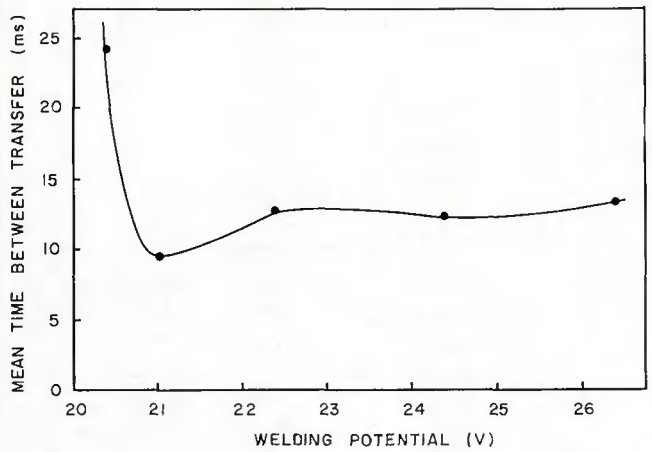

Fig. 6—Mean time between transfers as a function of welding voltage

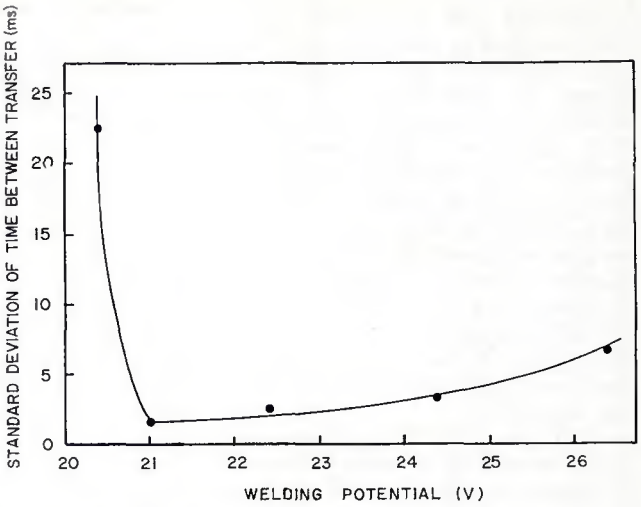

Fig. 7—Standard deviation of time between transfers as a function of welding voltage

tion had a narrow distribution and that the process was less erratic than at higher or lower voltage levels. Considering the maximum and minimum values of t_D (not just the value of the mean) further elucidate the behavior. At 20.4 V, the maximum value of t_D was 95.8 ms and the minimum was 6.6 ms. The maximums and minimums are plotted in Fig. 9 to show the significant differences in the arc behavior at different weld conditions.

In summary, welding parameters with the smallest variation in t_D were also those with the shortest transfer period, least spatter and smoothest bead surface.

Droplet-Transfer Rate

Droplet-transfer rate is a useful parameter to characterize any welding process. It provides information on the stability of the process, the rate of transfer, the size of the metal droplet being transferred and the behavior between transfer modes. Lesnewich (Ref. 5) performed all his studies at a constant arc length with varying arc current, electrode type and diameter. He determined that, as the welding current increased with increasing wire feed rate, there was also a gradual increase in the droplet transfer rate, which implies a smaller droplet size. At the transition current, Lesnewich (Ref. 5) noticed a significant change in the droplet transfer rate. However, the effect of welding voltage on droplet transfer rate could not be clearly shown. This study included a matrix of weldments which were prepared at almost constant current with varied voltages to examine the stability of the process and the metal-droplet transfer rate.

Droplet transfer rate (f_D) was defined as the inverse of the time period between two consecutive droplets ($1/t_D$). For each welding current and voltage combination, a range in droplet rate was observed. The distribution of the droplet rates could be used to indicate the stability of the process as an alternative to the transfer-time distribution. Obtained by inverting the average transfer times in Fig. 9, the droplet rates were plotted as a function of welding potential and current in Fig. 10. The maximum average droplet transfer rate was approximately 100 s^{-1}. The maximum transfer rate also corresponds to the voltage-current combination that is normally considered to be optimum (both in electrode data sheets and the judgment of welding operators) in terms of arc force, stability and sound.

Using the droplet transfer rate to estimate the average droplet size, it follows

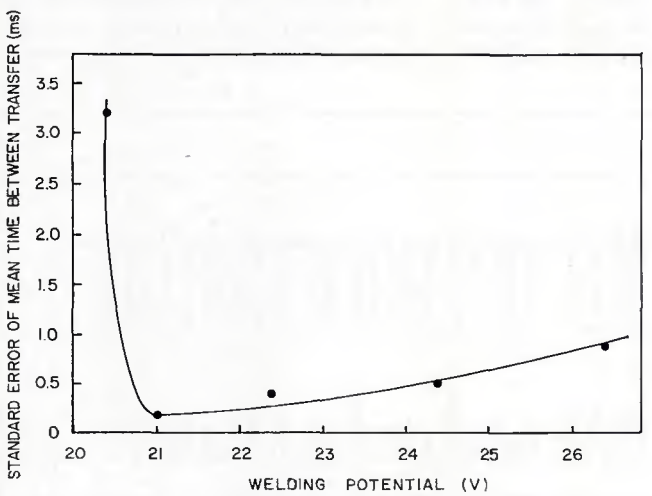

Fig. 8—Standard error of time between transfers as a function of welding voltage

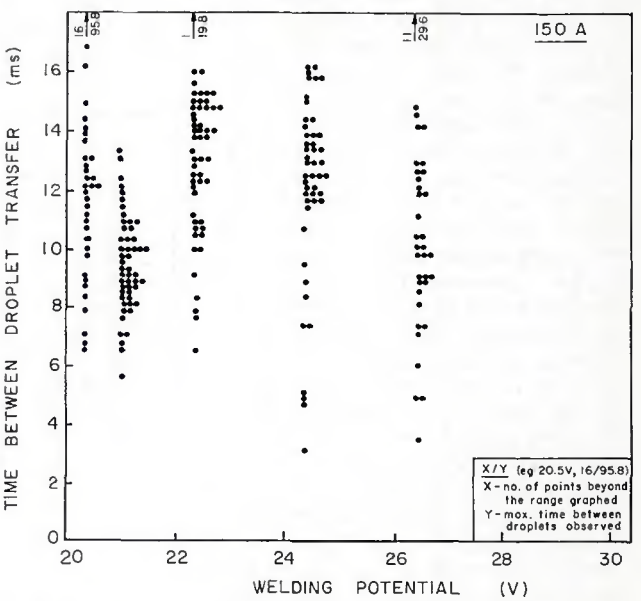

Fig. 9—Droplet-transfer period as a function of welding voltage

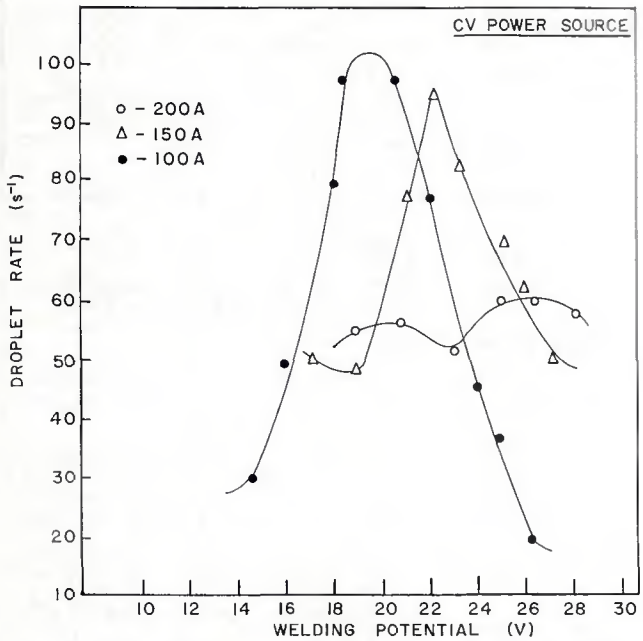

Fig. 10—Droplet rate as a function of welding current and voltage

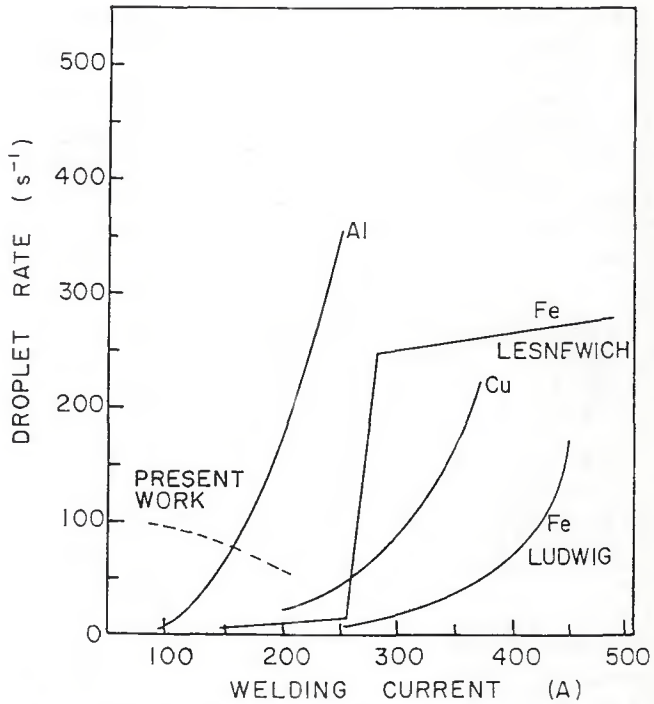

Fig. 11—Maximum droplet rate as a function of welding current

that the droplet size is a minimum at the maximum droplet rate. This implies that at the optimum combination of welding parameters, the droplets are minute and transferred at a high rate. Figure 11 is a plot that includes data of Lesnewich, Ludwig and this study, and shows significant variations in the droplet rate.

Influence of Welding Parameters on Metal Droplet Transfer

To further clarify the influence of welding parameters on the metal transfer behavior, the droplet-rate isopleths are mapped on a current-voltage graph in Fig. 12. By examination of this map, we can identify a current-voltage operating region corresponding to the maximum droplet rate. As the welding current was increased, the welding potential also had to be increased to maintain the maximum droplet-transfer rate. This maximum frequency range agreed well with the operating conditions suggested in the welding handbooks or by the consumable manufacturers. Minor discrepancies may be due to the individual characteristics of the different power supplies used in the different studies. The relationship between the maximum droplet rate and optimum welding conditions might be used to simulate a welder's skill in adjusting a power source. This relationship could be programmed into an intelligent controller which would maintain optimum arc performance as the welding conditions change. Furthermore, this might improve the response of a welding robot to changes in welding conditions due to wear of the contact tip or change in electrode type or heat.

Using the programming capability of the power supply, we also used a steeper slope to generate new sets of welds for the plotting of other current-voltage droplet rate maps. Results similar to those described previously were observed.

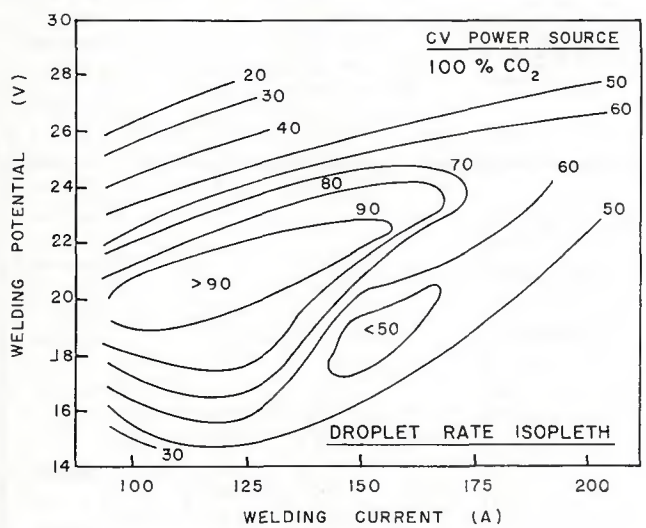

Fig. 12—Droplet rate isopleth for 100% CO_2 shielding

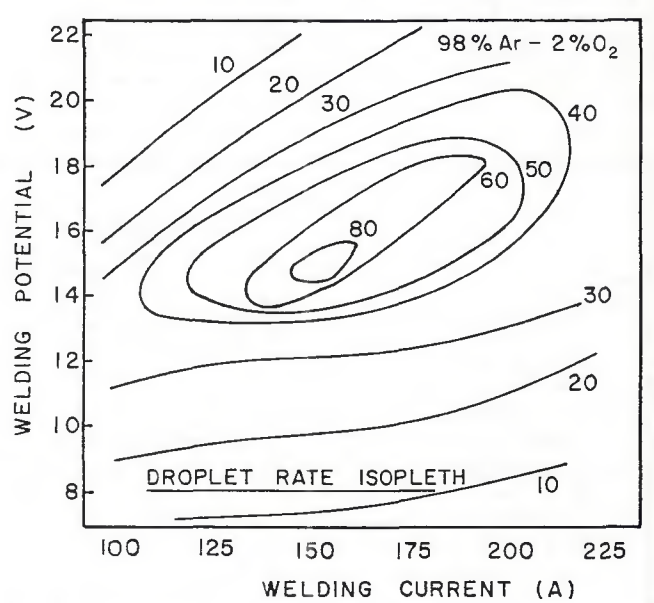

Fig. 13—Droplet rate isopleth for 98% Ar-2% O_2 shielding

The maximum rate range fit and compared well with the range of welding parameters specified in the manufacturers' electrode data sheets. Lower rates were found for longer arc lengths (higher voltages), per Lesnewich (Ref. 5). Indeed, this confirms that variations in experimental procedure (establishing a constant arc length versus a constant voltage) can easily explain the variations in transfer rate observed between previous studies.

In addition, 98% Ar-2% O_2 welds were examined and a similar plot was obtained—Fig. 13. This shows that for the 98% Ar-2% O_2 shielding gas, the same concepts applied. The overall lower rate may be attributed to the more stable arcing period in the transfer, as observed in the video recording. The maximum droplet rate varied from 45 s^{-1} at 100 A and 13 V to 90 s^{-1} at 200 A and 16.5 V

Besides affecting the transfer rate, the voltage controls the energy entering the weld pool. Welding voltage below the optimum value resulted in little superheating of the weld pool, which caused a crowned bead and sharp contours at the toe regions of the weld. Increasing the voltage to the optimum value led to a higher heat content and growth of the molten globules at the electrode tip. The weld-ripple pattern was smoother and less reinforcement was formed. Good bead appearance with smooth contours were observed. Increasing the voltage beyond the optimum range results in excessive growth of the globules of metal; it moves into a transition region of short-circuiting and globular mode. More spatter resulted.

For good gas metal arc welding operation, parameters corresponding to the maximum rate of metal-droplet-transfer rate should be specified to conjugate the maximum metal-droplet-transfer rate with the optimum bead morphology, and thus produce acceptable base-metal wetting.

Conclusions

1) Measurements of the arc current and voltage fluctuations during short-circuiting transfer enable quantitative measurement of the transfer stability.

2) The conditions of minimum fluctuation in droplet-transfer rate correspond to the lowest spatter and the least ripple; they are precisely the conditions chosen by a welder from the sound of the arc. This indicates that an intelligent controller can be designed to duplicate a welder's skill in balancing the welding voltage to the current.

3) Voltages above and below the optimum for a given current result in a lower average rate and a greater fluctuation in droplet rate.

4) For certain voltage-current combinations, the rate alternates between two values. This indicates that the transition between droplet-transfer modes is not smooth, but discontinuous.

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Accuracy of Stress Intensification Factors for Branch Connections
By E. C. Rodabaugh

This report presents a detailed examination of the stress intensification factor (SIF) formulations for perpendicular branch connections that are specified in American standard codes for use in the design of industrial and nuclear Class 2 and 3 piping systems.

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