Effect of Phase Control During Flashing on Flash Weld Defects

The use of electronic phase control to reduce flashing voltage is undesirable since smoother flashing is obtained with lower flashing voltages only if the voltage waveform is as close as possible to a full sinusoidal waveform

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Introduction and Historical Review

Flash-butt welding is a resistance welding process designed to produce a butt weld between two metallic interfaces of identical cross-sectional geometry.

A typical flash welding machine consists of four major parts:[1,2]

1. The machine bed, to which is attached the fixed platen with clamping assembly, and a set of insulated ways to support the movable platen.
2. The movable platen with clamping assembly, which is mounted on the electrically insulated ways.
3. A means for controlling the motion of the movable problem.
4. The welding transformer.

The typical sequence of operations employed in the production of flash welds is:[2]

1. The material being joined is clamped rigidly in the dies, and the specimens are separated by a suitable air gap.
2. The welding transformer is energized, providing a preselected open circuit voltage between the interfaces being joined.
3. The movable platen is advanced slowly until contact is made between two or more small protuberances on the opposing interfaces, thus providing a current path. The motion of the movable platen is continued, at a constantly accelerating rate producing many short-circuits randomly located over the opposing interfaces, each of which is terminated by rupture of the bridge as the molten metal produced is expelled. This portion of the process is known as the flashing portion, its objective being the establishment of a suitable temperature distribution in the work to assure proper forging action during the subsequent upset portion of the cycle.
4. The movable platen is accelerated rapidly by automatic application of an axial force of suitable magnitude causing intimate contact between the interfaces to be achieved rapidly and completely. This portion of the operation is known as the upset portion.
5. At some predetermined point, known as upset current cut-off, in the upsetting operation the welding transformer is de-energized, thus interrupting all further current flow through the joint.
6. After terminating upset, the clamps are opened and the welded assembly is removed from the machine.

The important flashing variables include:

1. The initial distance between the clamping dies, often called the initial clamping distance.
2 The platen displacement pattern such as linear flashing (constant platen velocity), parabolic flashing (constant rate of acceleration of the platen, which is the most widely used flashing pattern). Various special flashing programs have also been developed for specific applications.
3. The flashing voltage.
4. The material consumed during flashing, often called the flashing burnoff.

The important upset variables include:

1. The upset distance.
2. The upset force.
3. The flashing current cut-off time.

The temperature distribution for automatic flashing with full sinusoidal voltage waveform can be predicted satisfactorily from a knowledge of the material constants, the dimensions of the work and the flashing variables.[4] The proper choice of flashing variables should lead to the optimum temperature distribution at the instant of upset.

Previous work has shown the following:[1]

1. The lowest practical flashing voltage should be employed in all flashing operations in order to provide the smoothest possible flashing action.
2. Current flow during flashing is initiated by metallic contact between "high" spots and minute protuberances on the opposing flashing interfaces.
3. The current surge heats the individual short circuits to above their melting point and causes their expulsion. A portion of the heat is simultaneously transferred by conduction to the underlying solid interfaces.
4. The temperature distribution established in this portion has been shown to be unaffected[1] by flashing voltage for a full sinusoidal waveform.

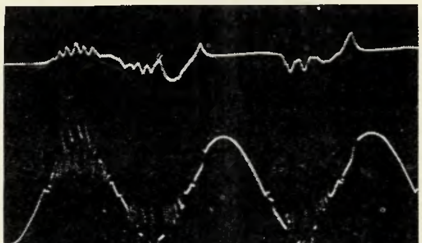

Fig. 1—Cathode ray oscillogram of secondary voltage and primary current waveforms during the flashing operation with 100% heat setting

Figure 1 is a cathode-ray oscillogram showing typical variations in the secondary voltage and the primary current during the flashing operation using essentially a full sinusoidal voltage waveform. Time proceeds from left to right. Referring to the current waveforms (upper trace) the following

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characteristics should be noted:

1. Current flow is intermittent and consists of randomly spaced surges of varying magnitude and duration.

2. Each small peak on the current waveform results from the making and expulsion of an individual short circuit between the interfaces.

3. Large current pulses of longer duration represent the making and expulsion of short circuits of significantly greater cross-sectional area than the average.

4. The rate of current build-up (leading edge of current pulses) is controlled by the inductive reactance of the secondary circuit and the magnitude of the secondary voltage at the instant the short circuit forms. In general, the effective inductive reactance is essentially constant for a given transformer tap setting and specimen geometry. However, the instantaneous open-circuit secondary voltage varies sinusoidally from zero to a maximum and returns to zero every half cycle ($^1/_{120}$ sec.). Thus, short circuits formed near the crest of the voltage waveform exhibit a more rapid rate of current increase than those made near the beginning or end of a half cycle.

5. The rate of current decay after the expulsion of a short circuit is more rapid than the rate of rise, but is not instantaneous, again because of the inductive reactance of the secondary circuit.

Referring to the voltage waveform, (lower waveform in Fig. 1), the following characteristics should be noted:

1. A voltage drop occurs in the secondary circuit during all intervals when the current is building up in the presence of one or more short circuits. This is merely an IR drop due to the internal resistance of the secondary circuit.

2. A sharp voltage spike is induced by the secondary whenever a short circuit blows-free and the induced voltage then decays exponentially in synchronism with the decay in secondary current. The magnitude of these spikes is often 20 v or more, (roughly the ionization potential of the atmosphere) and suggests that the current decay may occur by arcing between the weld interfaces. This phenomenon is attributable to the tendency for the terminal voltage of an inductive circuit to fluctuate instantaneously in order to prevent sudden changes in current. This induced voltage varies in accordance with the relationship:

$$e_L = -L\frac{di}{dt}$$

where: e_L = the induced voltage in volts; L = the inductance in henries; di/dt = the time rate of change in current in amp/sec.

Thus, when a small short circuit "blows-free" the component of secondary current responsible is prevented from decaying instantaneously to zero by the inductance of the circuit, and the voltage spike induced permits one to monitor each such event. In other words, each short circuit broken during the flashing operation provides a "signature" on the voltage waveform in the form of an inductive spike.

From the above discussion, it is obvious that much can be learned about the flashing operation by careful study of the current and voltage waveforms. The magnitude and duration of the current pulses are directly proportional to the size of the individual short circuits (or alternately the sum of the areas of individual short circuits, if more than one is active at a given instant). The interruption of each individual short circuit provides a signature spike on the voltage waveform even when other parallel short circuits remain active. Thus, from comparison of typical waveforms for flashing conducted under various conditions, it is possible to determine the effect of individual flashing variables on the overall flashing behavior. This, in fact, is the basic technique employed in the initial phase of the present investigation.

It is universally accepted that the best flashing action is obtained when the open-circuit secondary voltage is maintained at the lowest value possible without causing choking or butting of the flashing interfaces. The indicated RMS open circuit secondary voltage, as read on the usual measuring instruments, can be reduced by two methods:

1. Increasing the turns ratio of the welding transformer by means of a tap changing switch or auto transformer so that the ratio e_p/e_s is increased, where e_p and e_s are the primary and secondary open circuit voltages respectively.

2. Utilizing an electronic means of reducing the RMS voltage at the primary by modification of the voltage waveform. This technique, referred to as "Electronic Heat Control" or "Phase Control" utilizes a pair of ignitrons or SCR's in inverse parallel as a rapid-acting electronic switch to interrupt the primary supply voltage for a variable but reproducible interval during each half-cycle of supply voltage.

Typical voltage waveforms corresponding to two settings of the electronic phase control are shown in the schematic oscillograms in Fig. 2. The upper trace corresponds to a phase-control setting of 100%. The other waveform corresponds to a phase-control setting of 70%. It should be noted that:

1. The instantaneous voltage values during the ontime intervals are identical in both traces.

2. However, with a 70% heat setting no voltage is applied during approximately 20% of each half cycle. Note that although the peak voltages of both waveforms correspond to 7.07 v, the RMS voltages which one would read with either an iron-vane or an electrodynamometer voltmeter are 5.0 and 3.93 v for the 100% and 70% settings, respectively.

Savage[1] in an interpretive report on flash welding suggested that the use of electronic heat or phase control was poor practice since any short circuits formed during the off-time interval should grow as the platen advances in a continuous fashion. This in turn would require excessively large current pulses in order to clear the short

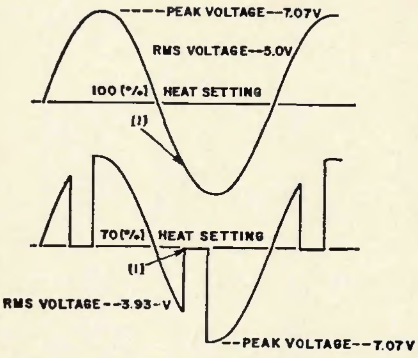

Fig. 2—Schematic representation of secondary voltage waveforms showing the effect of electronic phase control

Table 1—Summary of Fixed Variables Studied

Initial clamping distance	1.735 in.
Flashing burnoff	0.40 in./specimen
Current cut-off	7 cycles after upset
Primary voltage	415 v
Primary-secondary turns ratio	55:1
Open circuit secondary voltage (100% phase setting)	7.53 v

Table 2—Summary of Independent Variables Studied

Series No.	Upset distance, in.	Platen acceleration, in./sec^2
1	0.0	0.010
2		0.0027
3	0.10	0.010
4		0.0027
5	0.20	0.010
6		0.0027

circuit once secondary voltage appeared. This postulate has not been investigated in depth, however, and so was chosen as one subject for investigation during the present research.

Furthermore, the magnitude and duration of the current pulses are directly proportional to the size of the short circuit. Therefore, it seems logical that the character of the flashing interface should be adversely influenced by the use of phase control. Consequently, subsidiary investigations were undertaken of the effect of the use of heat control on the microstructure, properties and incidence of a type of weld defect known as flat spots, or, if they interest the weld surface, penetrators.

Objectives

The objectives of this investigation were to determine the effects of electronic phase control on:

1. The flashing voltage and current waveforms.
2. The overall flashing behavior.
3. The tensile properties of flash welds.
4. The metallographic structure, both at the weld interface and in the heat-affected zone of flash welds.

Material

The material used in this investigation consisted of AISI 1020 steel supplied in the form of hot-rolled bar stock 0.5 in. in diameter and 6 in. in length with a nominal composition of: carbon—0.18–0.23%; manganese—0.30–0.60%; phosphorous—0.040% maximum; sulfur—0.050% maximum; and iron—balance.

Procedure

Flash-butt welds were made on a 250 kva flash-butt welding machine set for automatic flashing. All flashing was performed using constant rates of platen acceleration to provide a so-called "parabolic flashing pattern." The fixed variables are summarized in Table 1. Welds were made using each of the combinations of platen acceleration and upset distance shown in Table 2 with flashing phase-control settings of 40, 60, 80, 90 and 100%.

Tensile properties and Vickers Pyramid Hardness properties of flash-butt welds were compared for welds made with the conditions listed in Table 2 for set-up numbers 3–6 at each of the five-phase control settings studied. Ten tensile specimens with a 0.40 in. reduced diameter at the weld line, produced by dressing at the weld line with a tool having a $^1/_4$ in. radius of curvature, were pulled for each of the 20 combinations of variables studied. The reduced cross section and the relatively large radius notch assured failure at the weld line.

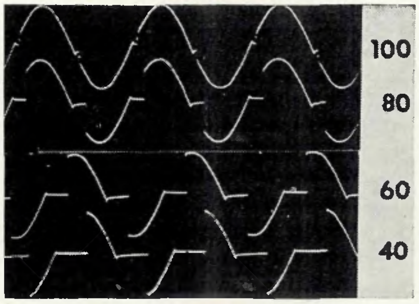

Fig. 3—Cathode ray oscillograms showing flashing voltage waveforms for the indicated electronic phase control settings

Metallographic specimens of representative flash-butt welds made with each combination of welding variables were prepared utilizing standard metallographic practice, and etched in a hot (160–200° F) saturated aqueous solution of picric acid. They were immediately washed in alcohol and dried in a stream of warm clean air.

Photomacrographs were taken at X10 magnification of the metallographic specimens to permit comparison of the macrostructures both at the weld line and within the weld heat-affected zone.

Cathode-ray oscillograms were taken of the primary current and secondary voltage displays on a dual-trace cathode-ray oscilloscope.

Oscillograms of the secondary voltage, primary current and platen travel for the entire flashing operation were also obtained using a standard, commercially available, direct-developing recording oscillograph.

The true RMS open circuit secondary voltage at different electronic phase control settings (100%, 90%, 80%, 70%, 60%, 50%, 40%) were measured with a 0-10 v moving-iron type voltmeter having an accuracy rating of $\pm\, ^1/_2\%$ of full scale.

Results and Discussion

The Effect of Electronic Phase Control on Flashing Voltage and Current Waveforms

Typical voltage waveforms corresponding to four settings of electronic heat-control are shown in the cathode ray oscillograms in Fig. 3. Time proceeds from left to right in the conventional manner. The upper trace corresponds to a heat-control setting of 100%. In theory this waveform should correspond to the full sinusoidal waveform of the welding supply voltage. However, it is rarely possible to diminish the off-interval to zero reproducibly without causing occasional misfiring of one or the other ignitron.

Table 3—Summary of the Characteristics of the Phased-Back Voltage Waveforms

Percent electronic heat control	Off-time/ cycle, millisec	Off-time/ cycle, %	On-time/ cycle, millisec	On-time/ cycle, %
100	0.60	7.0	7.73	93.0
80	1.83	22.0	6.50	78.0
60	3.10	37.2	5.23	62.8
40	5.02	51.7	3.31	48.3

The other three waveforms correspond to phase control settings of 80, 60, and 40% as indicated at the right margin. It should be noted that the on-interval per cycle in these oscillograms, taken directly from the flash welder used in this investigation, corresponds to 93, 78, 62.8 and 48.3% for phase control settings of 100, 80, 60, and 40%, respectively. From the opposite viewpoint, the off-times during which no flashing voltage is present correspond to 7, 22, 37.2 and 51.7% for phase control settings of 100, 80, 60, and 40% respectively.

A summary of the characteristics of the phased-back voltage waveforms is shown in Table 3. The off-time and on-time for each electronic heat control setting was obtained from the cathode ray oscillograms shown in Fig. 3.

Figure 4 depicts four cathode-ray oscillograms of the primary current and secondary voltage obtained during the flashing operation with phase settings of 100, 80, 60, and 40% respectively. The upper trace in each is the current waveform and the lower trace is the voltage waveform. In all cases time proceeds from left to right in the conventional manner.

Referring to Fig 4 the following pertinent observations can be made:

1. The number of voltage spikes, each indicating the expulsion of a momentary short circuit between the flashing interface (lower trace), tends to diminish from a maximum with 100% heat (Fig. 4A) to a minimum with 40% heat (Fig. 4D).

2. The magnitude of the individual current pulses increases (upper trace) as the phase control setting is reduced from 100% (Fig. 4A), to 80% (Fig. 4B) to 60% (Fig. 4C) to 40% (Fig. 4D).

3. The largest current pulses in all cases occur when a short circuit exists at the instant the voltage is restored following an off-time interval.

4. The maximum duration of the current pulses ranges from about 50% of the voltage on-time interval with 100% heat to 100% of the on-time interval for the 60% to 40% heat settings.

Table 4 summarizes the voltage du-

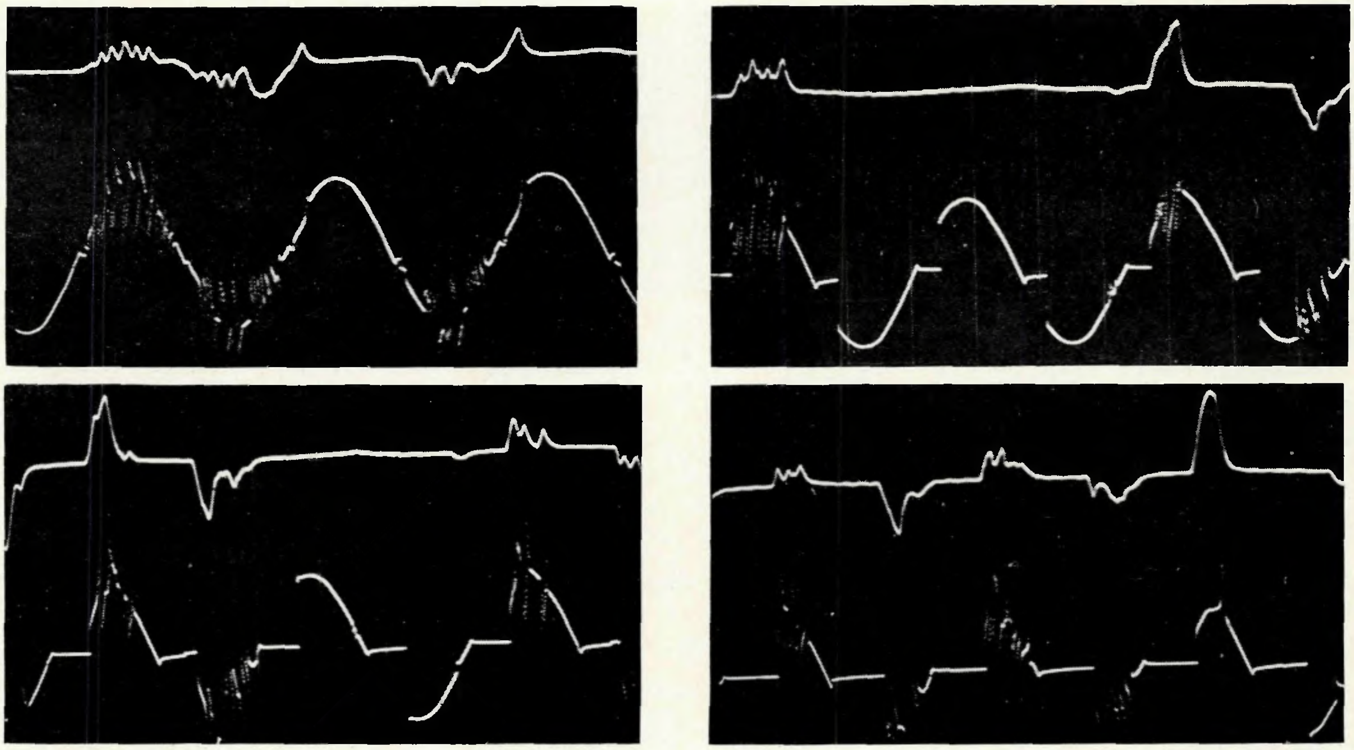

Fig. 4—Cathode ray oscillograms showing flashing voltage and primary current waveforms. A (top left)—100% heat setting; B (top right)—80% heat setting; C (bottom left)—60% heat setting; D (bottom right)—40% heat setting

ration, t_v, during each half-cycle of supply voltage, the maximum observed flashing duty cycle within any period of voltage on-time, r, and the maximum current for the four oscillograms contained in Fig. 4. Note that the maximum duty cycle increased from 50% with 100% heat to 100% for both the 60% and 40% settings as mentioned above. Note also that the peak currents observed were 5000, 9500, 12,500 and 13,000 amp for the 100, 80, 60 and 40% heat settings, respectively.

Although it should be emphasized that the oscillograms shown in Fig. 4 are not necessarily representative of the entire flashing interval, all were taken at the same point in the flashing pattern, and indicate a trend. On the basis of this trend, it appears that the use of voltage waveforms approximating a full sinusoid as closely as possible ensures that the short-circuits (or bridges) are expelled as quickly as possible with the smallest possible current build-up. This would imply that the flashing interface would be less likely to develop deep pits with the 100% heat setting than with any of the phased-back voltage waveforms. Since a lower probability of developing deep pits represents a desirable situation, it was decided to explore this trend further by taking oscillograms of the entire flashing period using a direct-developing oscillograph. In this way, the overall flashing behavior could be investigated.

Once oscillograms of the entire flashing operation were obtained for a platen acceleration of 0.0027 in./sec.^{2} using phase control settings of 100, 80, 60, and 40% heat, the following data were collected for a period of approximately 96 cycles immediately preceding the upsetting operations:

1. Total flashing time examined (cycles), N_t.
2. Number of cycles during which flashing events were observed (active flashing time, cycles), N_a.
3. Number of short circuits broken during the sampling period (based on the number of voltage spikes on the voltage trace), N_s.
4. Number of the short circuits which existed at the beginning of a voltage on-period, N_i.

Table 5 summarizes the results of this portion of the investigation and the data shown are based upon the average of data from the three duplicate runs at each phase control setting.

The sampling interval for each oscillogram was held constant at 96-half-cycle intervals (48 cycles) except for one run made with 40% heat during which butting or choking occurred necessitating that a shorter total flash time be chosen. This fact is reflected in the lower average time of 94-half cycles for this series. The active flashing time, N_a, as defined above, proved to be essentially independent of the phase setting within the experimental error. Note that one or more short circuits occurred in roughly 50% of the half-cycle intervals sampled; during the balance of the time no action was observed on the flashing interfaces (column 3).

The average number of short circuits, N_s, per sampling interval decreased continuously as the percent-heat setting was reduced, the observed values being 216, 193, 157 and 103 for phase control settings of 100, 80, 60, and 40% respectively (column 4). Of the total number of short circuits, the number existing at the start of a voltage on-time interval (i.e. the number of bridges formed during the off-time intervals, N_i) increased as the percent heat setting was reduced. (Refer to column 5 of Table 5.) The percentage of the total short circuits which formed during the off-

Table 4—Summary Data From Cathode Ray Oscillograms of Fig. 4

Phase setting, % heat	t_v Voltage duration per ½ cycle, millisec	r Maximum[a] duty cycle, % t_v	i_{max} Maximum current, amp
100	7.73	50	5,000
80	6.50	57.4	9,500
60	5.23	100	12,500
40	4.02	100	13,000

[a] Maximum duty cycle is defined as follows: r = 100 (maximum duration of continuous current flow/duration of secondary voltage per ½ cycle)

Table 5—Summary of the Effects of Electronic Phase Control Setting on Overall Flashing Behavior

Electronic heat setting, %	Total flash time, ½-cycle N_t	Active flash time, ½-cycle N_a	Number of short circuits, N_s	Number of off-time bridges, N_i	Off-time bridges per short circuit, %	Bridges per ½-cycle, avg.	Bridges per active ½-cycle	Bridges at start of active ½-cycles, %
100	96	48.3	216	10.0	4.63	2.25	4.47	20.6
80	96	46.7	193	39.6	20.5	2.04	4.10	84.8
60	96	52.0	157	46.0	29.3	1.64	3.02	88.4
40	94	46.3	103	42.0	40.8	1.10	2.27	90.8

Table 6—Effect of Phase Control on Open Circuit Secondary Indicated RMS Voltage

Electronic heat control, %	RMS voltage
100	7.53
90	7.46
80	7.20
70	6.82
60	6.23
50	5.49
40	4.72

time interval (refer to column 6) was obtained for each heat-control setting by dividing the data in column 5 by those in column 4.

Note that the percentage of the bridges formed during the off-time interval shows a definite trend. Note the values of 4.63, 20.5, 29.3 and 40.8% shown in column 6 for 100, 80, 60, and 40% respectively. This clearly indicates that, as would be expected, the longer off-time periods characteristic of phased-back waveforms increase the chances that a short circuit will form and grow during an interval when no voltage is present to initiate current and cause expulsion. Furthermore, since the same amount of material was flashed-off during each sample interval, the decrease in the number of short circuits formed as the percent-heat was reduced indicates that more material must have been removed per short circuit with the lower heat settings.

Columns 7 and 8 show the average number of bridges per half-cycle of total flashing time and active flashing time, respectively. Note the continuous decrease in short circuit events per cycle in both cases.

The data shown in column 9 of Table 5 are particularly significant. Note that these data, which were obtained by dividing the number of off-time bridges (column 5) by the number of active $^1/_2$-cycles (column 3), indicate that the probability of forming short-circuits during a voltage off-time interval increases rapidly even with a small reduction in the percent heat setting. Thus, the percentage of the bridges existing at the start of an active flashing interval increased from 20.6% with 100% heat to 84.8% with 80% heat. This in spite of the fact that the percent off-time (or "dead time") per cycle only increased from 7% to 22% for this reduction in heat-control setting (refer to Table 3). The corresponding values of the percentage of active half-cycles with short circuits present at the beginning for 60% and 40% heat are 88.4 and 90.8%, respectively. Note that the corresponding off-times are 37.2 and 51.7% for 60% and 40% heat (refer again to Table 3).

Table 6 summarizes the RMS voltage readings obtained for the phased-back voltage wave forms studied. Note that the 100% heat setting provided an indicated RMS voltage of 7.53 v while the 40% heat setting provided an indicated voltage reading of only 4.72 v. However, the data presented above clearly show that smoother flashing (i.e., more short circuits of shorter duration and smaller peak current) were observed with 100% heat than with 40% heat. In fact, the data showed that even at 80% heat (7.20 v RMS) the flashing behavior suffered severe degradation. Thus, it appears that the practice of attempting to "reduce" the flashing voltage by means of phase control is not sound, and that *smoother flashing is obtained with lower flashing voltages ONLY if the voltage waveform is as close to a full sinusoid as possible. The data clearly show that even a moderate reduction of the heat-control setting increases the probability of creating a disproportionate number of large short circuits, which, in*

Table 7—Longitudinal Tensile Properties of Series 3[a]

Phase setting, %	Yield point, psi	Ultimate tensile strength, psi
100	57,230	71,230
	σ = 331	σ = 1220
90	56,830	69,820
	σ = 289	σ = 1670
80	58,530	69,450
	σ = 447	σ = 1530
60	55,720	66,380
	σ = 480	σ = 1850
40	56,180	63,400
	σ = 621	σ = 2850
Control	57,250	72,175
	σ = 450	σ = 533

[a] Upset—0.10 in.; platen acceleration—0.0027 in./sec².

Table 8—Longitudinal Tensile Properties of Series 4[a]

Phase setting, %	Yield point, psi	Ultimate tensile strength, psi
100	57,100	71,800
	σ = 372	σ = 1100
90	56,800	71,600
	σ = 246	σ = 1850
80	54,600	68,900
	σ = 437	σ = 1735
60	55,400	64,200
	σ = 155	σ = 1946
40	56,900	63,300
	σ = 510	σ = 2350
Control	57,250	72,175
	σ = 450	σ = 533

[a] Upset—0.10 in.; platen acceleration—0.01 in./sec².

Table 9—Longitudinal Tensile Properties of Series 5[a]

Phase setting, %	Yield point, psi	Ultimate tensile strength, psi
100	58,130	72,630
	σ = 182	σ = 1170
90	57,600	70,820
	σ = 568	σ = 1590
80	58,010	67,530
	σ = 387	σ = 1430
60	55,700	67,800
	σ = 480	σ = 1930
40	56,180	65,230
	σ = 288	σ = 2370
Control	57,250	72,175
	σ = 450	σ = 533

[a] Upset—0.20 in.; platen acceleration—0.0027 in./sec².

Table 10—Longitudinal Tensile Properties of Series 6[a]

Phase setting, %	Yield point, psi	Ultimate tensile strength, psi
100	57,300	72,300
	σ = 420	σ = 912
90	58,200	69,400
	σ = 755	σ = 2430
80	58,470	69,500
	σ = 320	σ = 1200
60	57,830	67,860
	σ = 220	σ = 1700
40	57,400	65,270
	σ = 700	σ = 2310
Control	57,250	72,175
	σ = 450	σ = 533

[a] Upset—0.20 in.; platen acceleration—0.010 in./sec².

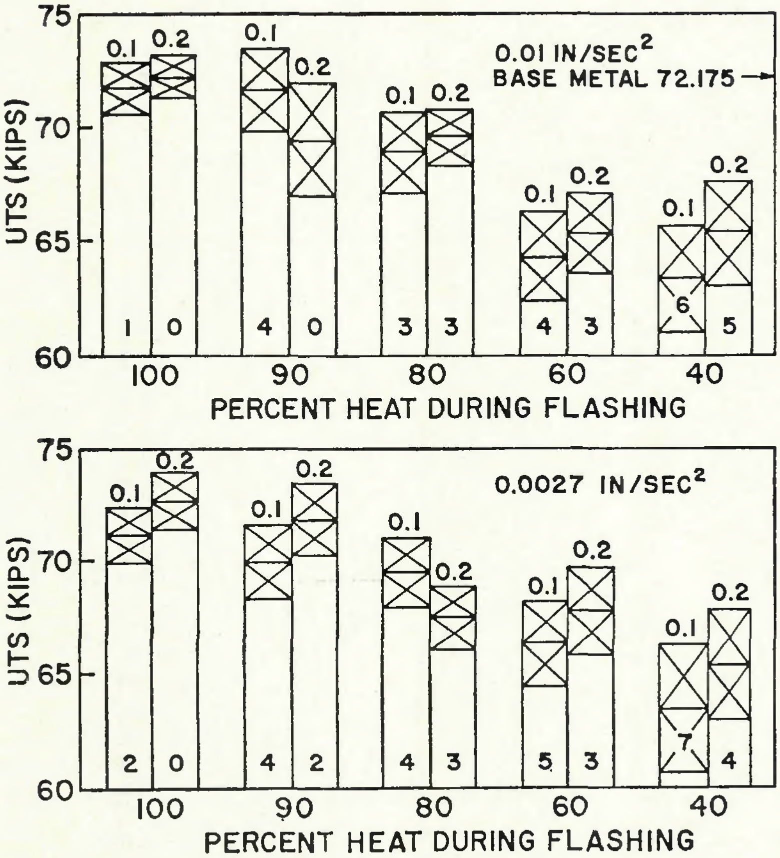

Fig. 5—Effect of upset distance on ultimate tensile strength for indicated values of platen acceleration during flashing

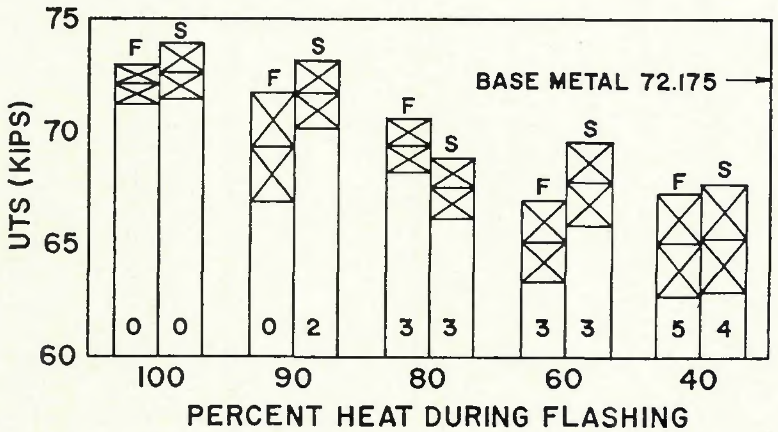

Fig. 6—Effect of platen acceleration on the ultimate tensile strength for constant upset distance of 0.20 in. F—fast acceleration, 0.01 in./sec²; S—slow acceleration, 0.0027 in./sec²

Table 11—Summary of the Effects of Electronic Phase-Control on Welding Defects

Electronic phase setting, %	Number of specimens with weld defects for the following conditions — Based upon ten specimens per electronic phase setting: 0.10 in. upset 0.0027 in./sec.² platen acceleration	0.10 in. upset 0.01 in./sec.² platen acceleration	0.20 in. upset 0.0027 in./sec.² platen acceleration	0.20 in. upset 0.01 in./sec.² platen acceleration
100	2	1	0	0
90	4	4	2	0
80	4	3	3	3
60	5	4	3	3
40	7	6	4	5
Total	22	18	12	11

turn, are likely to leave deep liquid-filled pits on the flashing interface when eventually expelled.

Tensile Test Results

Tables 7-10 summarize the tensile test results for the flash welds from Series 3-6, respectively (refer to Tables 1 and 2 for welding conditions). The yield point and ultimate tensile strength data shown in these tables represent the average of ten tests at each set of welding conditions. Also included in the table are values of the standard deviation, σ, for each average value.

Since all measured values of yield point lie well within $\pm$ 2 σ of the overall average, it appears unlikely that any of the combinations of platen acceleration, electronic-phase-control setting and upset distance had a significant influence on the yield point. This is, however, not surprising, as the presence of minor weld defects such as flat spots and/or penetrators rarely has a significant effect on the yield point in a flash weld in a plain carbon steel such as AISI 1020.

In addition, it should be noted that the variance in the yield point as estimated from the values of the standard deviation does not show any significant trend. (Note that the values of σ for the yield point in Tables 7–10 range in a random fashion from about 155 to 755 psi.)

There does appear to be a significant influence of heat-control setting on the ultimate tensile strength values, however. This is best observed by reference to Fig. 5 which summarizes the data for the ultimate tensile strength of the welds in bar graph form. Note that the two cross-hatched regions at the top of each bar represent a variation of one standard deviation above and below the average value. Thus, the horizontal line between the two cross-hatched regions corresponds to the average value of the ultimate tensile strength shown in Tables 7–10.

The bars of Fig. 5 summarize the data obtained for two different upset distances (0.10 and 0.20 in. as indicated above each bar) at each of five different heat-control settings (100, 90, 80, 60, and 40% heat (as indicated below each pair of adjoining bars). The upper set of bar graphs represent welds made with a platen acceleration of 0.01 in./sec.², while the lower set represent welds made with a platen accleration of 0.0027 in./sec.².

Three trends should be noted for each value of platen acceleration:

1. The average value of the ultimate tensile strength tends to decrease as the percent-heat setting is dimin-

ished.

2. The standard deviation is least for welds made with a heat-control setting of 100%, and greatest for welds made with 40% heat.

3. In eight out of the ten pairs of data shown, for a given platen acceleration and heat-control setting, the welds made with 0.1 in. upset exhibit a lower average ultimate tensile strength than the welds made with 0.2 in. upset.

The number of specimens from each group of ten welds containing flat spots and/or penetrators is indicated by the numeral within each bar near its base. It is of interest to note that none of the twenty tensile specimens made with a heat-control setting of 100% and an upset distance of 0.2 in. showed any flat spots. However, five out of ten welds made with a platen acceleration of 0.01 in./sec.^{2} and an upset distance of 0.2 in. showed penetrators and/or flat spots when the electronic heat-control was set for 40% heat. With 0.2 in. upset and 0.0027 in./sec.^{2} platen acceleration, 4 out of 10 welds made with 40% heat showed flat spots and/or penetrators.

When the upset distance was reduced to 0.1 in. the number of specimens containing such defects within each group of ten duplicate welds was greater than the corresponding set of ten welds made with 0.2 in. upset (except for the case of the welds made with 80% heat and a platen acceleration of 0.01 in./sec.^{2}, where the number was the same for both values of upset).

Figure 6 compares the values of ultimate tensile strength for welds made using 0.2 in. upset with each value of the heat-control setting for the two values of platen acceleration studied. In each case, the left hand bar in each pair (F) represents the data for the faster acceleration and the right hand bar (S) represents that for the slower acceleration. Note that in every case the two average values fall within one standard deviation of one another. This suggests that the platen acceleration did not exert a significant influence on the ultimate tensile strength, at least within the range studied, (0.0027–0.01 in./sec.^{2}). In addition, the data on the incidence of flat spots and/or penetrators do not differ sufficiently to indicate that changing the platen acceleration significantly influenced the formation of such defects.

Table 11 summarizes the incidence of flat spots and/or penetrators within each group of 10 welds made under identical conditions. Attention is drawn to the fact that of the total of 100 welds tested which were made with 0.1 in. upset a total of 40 (or 40%) contained either flat spots or penetrators. On the other hand, of the 100 welds made with 0.2 in. upset, only 23 (or 23%) contained penetrators and/or flat spots. This strongly suggests that inadequate upset can contribute to the formation of such defects.

Metallographic Examination

By eliminating the upset operation, a series of specimens were subjected to the flashing operation only. By sectioning a series of such specimens (prepared using heat-control settings of 100, 90, 80, 60 and 40%) along the longitudinal centerline, it was possible to study the effect of the heat-control setting on the condition of the interface at the end of the flashing cycle. The specimens were etched in a hot, saturated aqueous solution of picric acid and examined for evidence of solidification substructure (which indicates the presence of molten material on the interface at the end of the flashing cycle).

Figures 7–9 typify the appearance of the flashing interface after a flashing burn-off of 0.8 in. (0.4 in./specimen) with a platen acceleration of 0.010-in./sec.^{2} using 100, 90 and 80% heat, respectively. The light etching regions along the interface in these photomacrographs (taken at X10 magnification) exhibited a solidification substructure when viewed at higher magnification and thus represent the extent of the liquid film present on the interfaces at the end of the flashing operation.

It should be noted that:

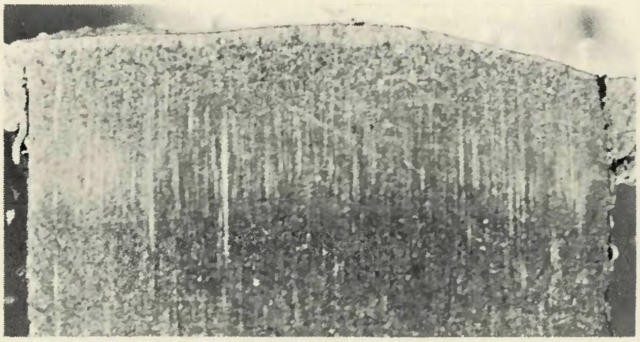

Fig. 7—Photomacrograph of specimen, sectioned along the longitudinal centerline, made at 100% electronic phase control setting with no upset and 0.01 in./sec^2 platen acceleration. Etched in a hot saturated aqueous solution of picric acid

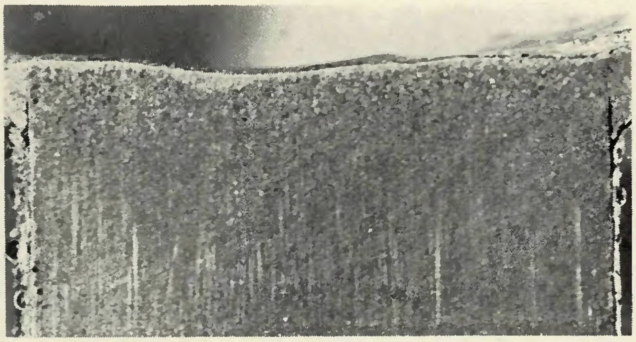

Fig. 8—Photomacrograph of specimen, sectioned along the longitudinal centerline, made at 90% electronic phase control setting with no upset and 0.01 in./sec^2 platen acceleration. Etched in a hot saturated aqueous solution of picric acid

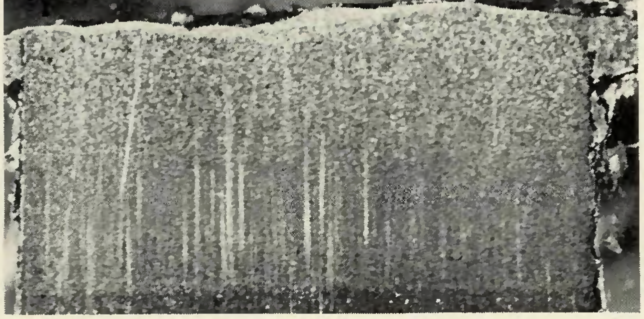

Fig. 9 (right)—Photomacrograph of specimen, sectioned along the longitudinal centerline, made at 80% electronic phase control setting with no upset and 0.01 in./sec^2 platen acceleration. Etched in a hot saturated aqueous solution of picric acid

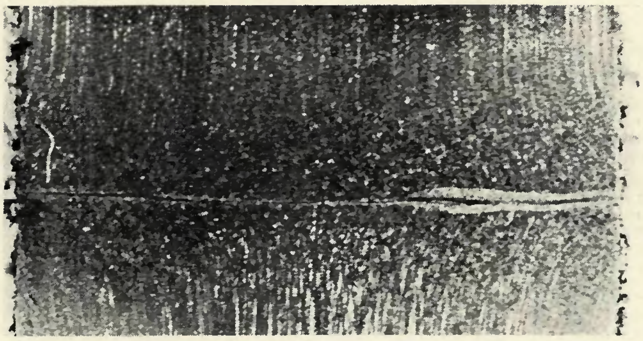

Fig. 10—Photomacrograph of specimen, sectioned along the longitudinal centerline, made at 80% electronic phase control setting with 0.10 in. upset and 0.01 in./sec^2 platen acceleration. Etched with a hot saturated aqueous solution of picric acid

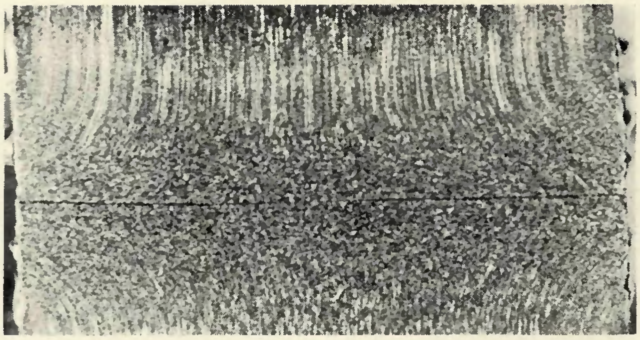

Fig 11—Photomacrograph of specimen, sectioned along the longitudinal centerline, made at 80% electronic phase control setting with 0.20 in. upset and 0.01 in./sec^2 platen acceleration. Etched in a hot saturated aqueous solution of picric acid

1. With 100% heat, the interfaces were normally smooth and regular in appearance and the liquid layer was relatively uniform in thickness over the entire surface as typified by Fig. 7.

2. With 90, and 80% heat, however, the interfaces invariably showed one or more relatively deep liquid-filled craters such as are visible about one-third of the way in from the left in Fig. 8 and near the center in Fig. 9.

Both the depth and frequency of appearance of these liquid-filled craters increased as the heat-control setting was further reduced to 60 and 40%. Therefore, it is proposed that the deep craters are formed by the expulsion of short circuits formed during the off-time interval period of the phased-back waveform when no secondary voltage is present. Short circuits formed during such off-time intervals tend to grow in area before the secondary voltage reappears and thus require large magnitude current bursts for their removal. The inductance of the secondary then limits the rate of decay of the current after expulsion of the short circuit and this explains the increased incidence of deep craters on the interface. This proposed mechanism is entirely consistent with, and is supported by, the observations reported in the earlier section on the oscillographic measurements of the current and voltage waveforms.

In order to establish if the existence of deep liquid-filled craters on the flashing interface could lead to the formation of flat spots and/or penetrators, a second series of flash welds was made using two different amounts of upset for various heat-control settings. These welds were subsequently sectioned along the longitudinal centerline, polished and etched as before and examined metallographically.

Figure 10, a photomacrograph at X10 magnification of a weld made with a platen acceleration of 0.010 in./sec.^{2}, 0.8 in. flashing burn-off, an 80% heat-control setting and a small (0.1 in.) upset shows a light etching region on both sides of the weld interface which exhibited a characteristic solidification substructure. Thus, it is certain that the material in this region was molten at the instant of upset initiation, presumably as a result of a massive short circuit which must have occurred near the end of the flashing operation. Note that the egress of the molten material in this region was completely blocked at the left hand side and nearly so at the right hand side of the cross-section by the initial stages of upset.

Although such crater-like regions containing liquid metal undoubtedly solidify almost immediately after the instant of current cut-off during upset, the difference in etching behavior as compared to the unmelted surroundings indicates that their composition was modified while in the liquid state. This is entirely understandable and consistent with theory, since:

1. The solubility of both solute elements and gases in the liquid-base metal contained within such craters differs significantly from that of the underlying solid base metal.

2. The diffusion rate in the liquid phase is several orders of magnitude faster than that in the solid phase just below the melting temperature. Thus, it is likely that the composition of the liquid contained within such craters does in fact differ significantly from that in the adjacent solid, as a result of both the partitioning of solute elements between the solid and liquid phases and the reactions occurring between the liquid phase and dissolved gases from the ambient atmosphere.

It is important to note that, if such a pocket of liquid of modified composition exists on the interfaces at the instant of upset, the initial stages of upset tend to seal it off and prevent its expulsion from the weld interface. Therefore, the entrapped liquid tends to solidify in-situ when current cut-off occurs. Once entrapped in this fashion, the isolated region of modified composition is deformed into a microscopically thin layer at the weld interface by the plastic deformation associated with the upsetting action. However, because of the modification of its composition produced while in the liquid state, the material would be expected to exhibit properties significantly different from those of the adjacent, unmodified base metal.

Figure 11 is a photomacrograph of a weld made with the same conditions used for the weld shown in Fig. 10 except that the upset distance was increased to 0.2 in. Note that no evidence of a liquid-filled crater remains in Fig. 11.*

Of course, the probability exists that no liquid-filled crater existed on the interface at the instant of upset in the specimen shown in Fig. 11. However, since such regions were almost invariably noted in specimens made with a phased-back voltage waveform using 0.1 in. upset, it seems probably that similar regions existed at the instant of upset but were flattened beyond recognition by the increased plastic deformation accompanying the 0.2 in. upset.

Microhardness tests conducted on typical welds indicated a hardness decrease of about 148 VPN at the weld interface. Furthermore, the material at the interface appears to have been decarburized slightly. This would be expected if oxygen from the ambient atmosphere dissolved in the liquid and was able to diffuse throughout the liquid contained in the crater. The dissolved oxygen would tend to react with the carbon, thus explaining the

*It should be noted that the dark appearing bands at the weld interface in the photomacrographs are regions of high reflectance which scattered the oblique lighting used to illuminate the specimen out of the objective lens, thus making the regions appear dark. When viewed under vertical illumination, these same regions are bright.

apparent decarburization. Furthermore, it is known that oxygen in solution embrittles steel. Therefore, if oxygen-rich liquid were entrapped then spread into a localized film during upset, this could readily explain the origin of so-called flat spots or penetrators.

In summary, then, the following model is proposed to explain the origin and nature of flat spots and/or penetrators:

1. During flashing, which consists of a random sequence of intermittent short circuits, the current consists of myriads of intermittent bursts whose magnitude and duration is directly proportional to the area of the short circuit.

2. The inductance of the welding transformer prevents the instantaneous decay of the current passing through a short circuit at the instant the metal forming the electrical bridge is expelled.

3. A portion of the heat generated during the expulsion of the bridge and the subsequent interval of current decay is transferred to the flashing interface and creates a liquid-filled crater whose size and depth is proportional to the cross-sectional area of the "bridge" at the instant of expulsion.

4. The composition of the liquid metal in the crater so-formed is modified both by diffusion of solutes present in the underlying base metal and by reaction with gases in the ambient atmosphere.

5. During upset the liquid from some of the deeper craters is denied egress from the weld interface, solidifies, and is plastically deformed to produce a thin, localized region of modified composition at the weld interface.

6. When a load is applied, this thin localized region of modified composition tends to rupture prematurely to produce a characteristic region with a "flat" fracture surface.

7. If the localized region of modified composition is entirely contained within the cross-section, the region of the flat fracture is termed a "flat spot."

8. If the localized region of modified composition extends to a free surface, the region of flat fracture is termed a penetrator.

With regard to the influence of electronic phase control during flashing, the following generalizations can be made:

1. The use of a phased-back voltage waveform, with periodically repeating intervals during which no secondary voltage appears at the dies increases the probability of forming short circuits with large cross-sectional area and thus of forming relatively deep liquid-filled craters on the interface.

2. This in turn increases the probability of entrapping liquid of modified composition at the weld interface and increases both the incidence and the size of flat spots and/or penetrators.

3. The formation of bridges or short circuits is random with time but, if formed during an off-time period, growth of the bridges occurs as a result of the continuous forward motion of the platen during flashing.

4. The extent of such growth should be minimized by:

(a) Utilizing a full sinusoidal waveform of secondary voltage (100% heat) so that current buildup can begin the instant the bridge forms.

(b) Minimizing the inductance of the welding transformer secondary so that the current can fluctuate rapidly, both to expel new bridges as quickly as possible before further growth in size can occur, and to permit current decay to occur as rapidly as possible following expulsion of the bridge.

Unfortunately, even with 100% heat it is statistically probable that an occasional bridge will form which is large enough to cause a flat spot or penetrator. However, the results of this research indicate that the probability of such an event occurring increases rapidly as the heat-control setting is reduced below 100%.

Conclusions

1. The practice of attempting to reduce the flashing voltage by means of electronic phase control is undesirable, since:

(a) Smoother flashing is obtained with lower flashing voltages *only* if the voltage waveform is as close to a full sinusoidal waveform as possible.

(b) Even a moderate reduction in the electronic heat-control setting increases the probability of creating a disproportionate number of large short circuits, causing deep, liquid-filled pits to be formed on the flashing interface.

2. The average value of the ultimate tensile strength decreases as the heat-control setting is diminished.

3. The standard deviation in ultimate tensile strength is least for welds made with a heat-control setting of 100% (essentially a sinusoidal waveform) and greatest for welds made with 40% heat-control setting.

4. The welds prepared with 0.20 in. upset showed better average ultimate tensile strength than did the welds prepared with 0.10 in. upset.

5. The probability of flat spots and/or penetrators occurring is greatly increased both by utilizing electronic heat-control during flashing and by inadequate upset distances.

6. A model has been proposed based upon secondary current characteristics and metallographic studies to explain the origin and nature of flat spots and/or penetrators.

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