Some Fundamental Problems in Percussive Welding

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The basic processes of percussive welding are presented. Large variations in arc duration result from the spread in initiation separation, magnetic bridging effects, and the amplifying effect of evaporation. Higher voltages are shown to decrease the relative spread of initiation separation. An analysis of bridging suggests minimizing the ratio of current to separation. A welding circuit offering independence from arc-duration variations is developed. The use of a capacitative transmission line, or approximations thereto, has resulted in greatly improved process control.

INTRODUCTION

Early work in percussive welding goes back to late in the nineteenth century. Both applications and accounts in literature are relatively rare. However, this type of welding should have considerable applicability in view of some rather outstanding advantages:

1. The fact that the arc potential is approximately 15 volts permits the addition of considerable energy within a very short time and, relative to resistance welding, small currents for shorter times are possible. This allows the welding electrodes to be placed well away from the weld zone without overheating of adjacent areas. Effects of deflection due to the high electrode clamping forces can be minimized.
2. The compatibility problem between the materials and geometries of the parts to be welded are eased relative to the slower butt welding method.
3. The welds produced in a controlled process are quite strong and can well approach the intrinsic strength of the parts to be welded.
4. The percussive welding process is very fast. Use in high speed automatic production is advantageous.

The problem treated in this paper arose during a very short study program at Bell Telephone Laboratories, Inc. in connection with a new relay development.* The paper, therefore, does not purport to be a thorough study of all phenomena of interest. The purpose is rather to enumerate the major fundamental problems and to present first order solutions. Perhaps other groups having further interest in the process will carry on basic research along the lines indicated.

BASIC PROCESS

Basically the process consists of an electrical circuit which stores energy and maintains a voltage across the two parts to be welded. This is illustrated in Fig. 1 where a wire is to be welded to a small rectangular block. A mechanical appendage, the "gun," holds one of these parts and moves towards the other, stationary part. At a separation x_0, the arc initiation separation, the airgap breaks down and the arc is initiated. While the arc heats the opposing surfaces, forming a thin layer of molten metal on both parts, they are being brought closer together and finally come into contact, extinguishing the arc. The joint now cools and the weld is made.

A properly controlled process poses two design problems. First, it is necessary to select materials that are reasonably compatible and geometries which allow each part to reach the desired temperatures. The second design problem is the choice of the proper electric circuit. This paper is primarily concerned with the latter problem.

Material selection may be dictated by other considerations, but it is necessary to choose materials which are capable of producing a sound joint. Irregularities, such as gas pockets, possibly due to a low boiling point component are to be avoided. Geometries must be chosen such that in the presence of heat conduction away from the surfaces to be welded, the average temperatures of both surfaces exceed their melting points but stay below their boiling points.

A proper electric circuit for percussive welding has to supply sufficient energy to produce thin molten layers on both parts. It is undesirable to

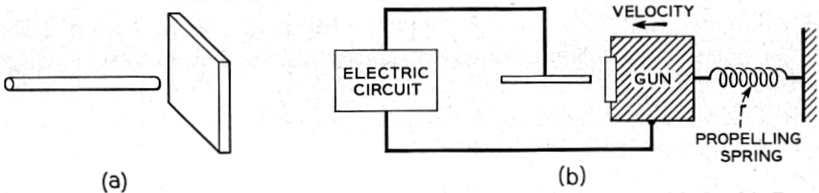
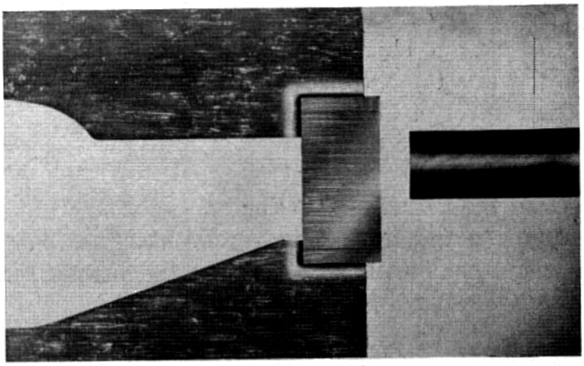
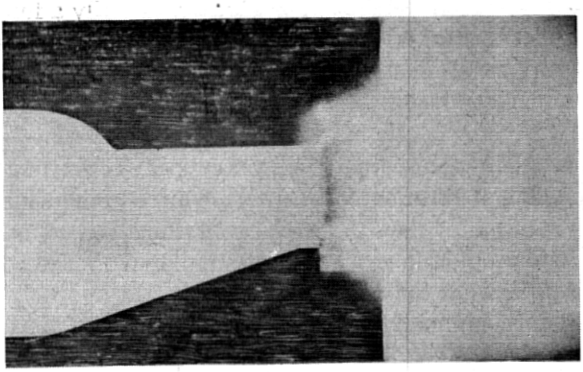


Fig. 1 (a) and (b) — Percussive welding. (a) Parts to be welded. (b) Process diagram.

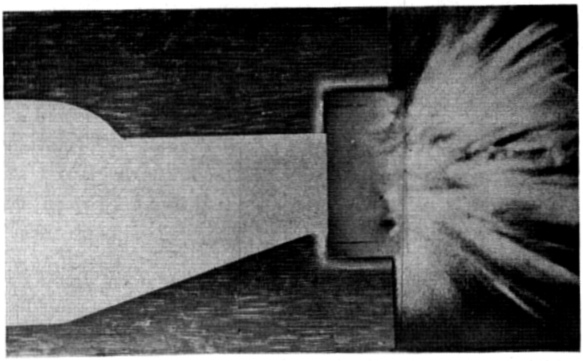
* A. C. Keller, A New General Purpose Relay for Telephone Switching Systems. B.S.T.J., pp. 1023–1067. November, 1952.



APPROACH



ARC



FOLLOW

Fig. 1 (c) — High-speed photographs of welding operation.

supply excessive energy because of the large amounts of material that are then burned off, and objectionable weld flash is produced. Probably the major problem is to control the energy supplied by the circuit or, indirectly, the control of arc duration.

DURATION OF ARC

In this section the variables affecting arc duration will be discussed. During the arcing period the gun moves essentially at constant speed. The arc time may then be said to be equal to the distance traveled after arc initiation divided by the gun velocity.

A. Initial Separation

The voltage at which the arc is initiated is primarily a function of the separation between the two electrodes. A series of static voltage breakdown tests was made in order to define the distribution of initiation separation under conditions to be expected in production welding of a block to a wire. The block material was 70-30 per cent cupro-nickel. The wire was 0.040-inch diameter silicon copper. Tests were taken with the wire end flat or terminated in a 60° conical point while the block surface was maintained flat. Industrial contamination as may very well be present in a productiln machine was simulated by the addition of a thin oil film on each of the opposing surfaces.

The results are summarized in graph form in Fig. 2. Plotted are the three σ limits* for the conditions indicated. Better arc initiation separation control is obtained with flat as compared with pointed wire ends, and clean as compared with oil contaminated wire ends. The ratio of maximum to minimum arc initiation separations to be expected is considerably lower for high voltages than low voltages. This fact alone makes operation at voltages in excess of 1,000 volts desirable.

In addition there exists an initiatory time lag† between the time that the separation reaches the static breakdown value and the moment of actual initiation. Arc duration variations due to this phenomenon are reduced by an increase in applied voltage.

B. Evaporation of Material

The arc does not cover the whole surface but is concentrated on a small area which is being heated, therefore, at a rate considerably in

* All but three out of 1,000 welds are expected to fall within these limits. It is to be noted that in view of the high reliability often required of this type of weld, conditions even further removed than three σ limits may have to be considered.

† Field Emission of Electrons in Discharges by Llewellyn, Jones and E. T. de la Perrelle, Proc. Roy. Soc. A, **216,** p. 267, 1953.

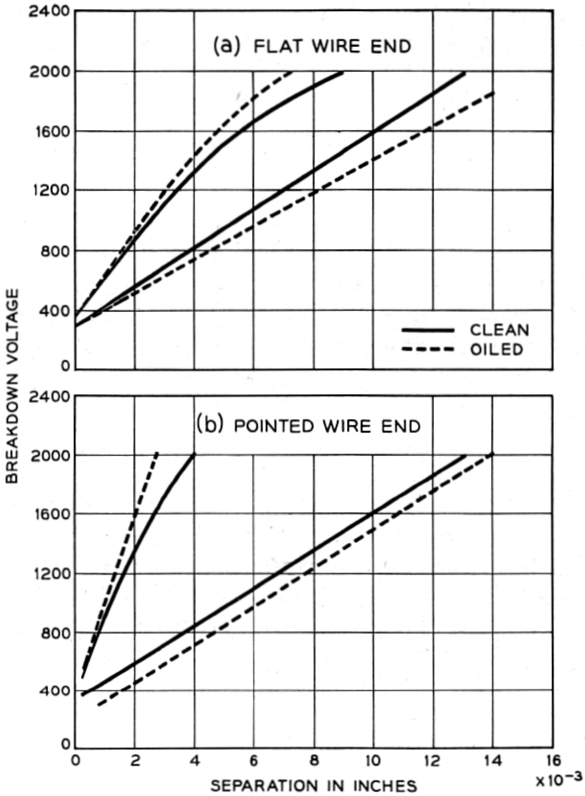


Fig. 2 — Three sigma limits of breakdown voltages between a plane surface and (a) a flat end and (b) pointed end of a round cross-section wire.

excess of that which one would compute as average heating. As a result very high temperatures occur in the arc region and material is evaporated. This somewhat increases the arc length and the arc moves on to a new spot. As a result of this mechanism some material is burned off in the arcing period and the arc duration is therefore longer than the initiation separation divided by the approach velocity. It is quite difficult to predict the amount of material evaporated. In lieu of more extensive experiments it can be stipulated that the evaporated material should be proportional to the energy input minus the energy directly radiated to the surroundings.

It is of interest, however, to note that the phenomenon of evaporation tends to increase the spread of arc duration as computed from the initiation separation alone. This is simply due to the fact that a large initiation separation means a longer arc duration, providing a larger energy input and hence increased evaporation. This means that the moving part has to travel further before the arc is extinguished thus further increasing the arc duration.

C. Bridging

Early experiments indicated a variation in arc duration greater than that which could be explained on the basis of variation of initiation separation and burn-off alone. It was realized that there was a third phenomenon involved. This phenomenon in which metal filaments form and extinguish the arc prematurely will be called bridging. As a demonstration of bridging the two surfaces to be welded were spaced 0.002 inches apart and voltage applied between them. The resultant arc produced a molten filament between them and a weld was formed.* With the materials used the welds produced were somewhat porous and not too strong but tests were much too fragmentary to properly evaluate this process.

Electrostatic forces are too small to account for the bridging phenomenon. A speculative explanation on the basis of magnetic forces may be attempted. Let us first examine a uniform liquid filament carrying a current I. Application of the electromagnetic stress tensor demonstrates the presence of radially compressive pressures equal to:

$$P = \frac{\mu_0 I^2 r^2}{8\pi^2 a^4}, \tag{1}$$

where

I equals total current carried by filament.
r equals radial distance from center of filament.
μ_0 equals permeability of filament material.
a equals radius of filament.

In the presence of these compressive stresses the filament will tend to elongate. Consider now the two surfaces of the parts to be welded covered with a thin film of molten material. If due to the turbulence caused by the arc a small filament forms on one surface it may tend to elongate in the presence of magnetic forces and bridge the gap between the surfaces. A detailed dynamical analysis of the formation and stability of these metal bridges is quite difficult. The following treatment is a very rough

* This may actually be an alternate method of welding with the advantage of offering excellent dimensional control.

model which will show that consideration of the magnetic forces does yield an explanation verifying the order of magnitude of the bridging observed in experiments.

The model simulates the bridging phenomenon by the translational motion of a small cylindrical filament across the gap between the two surfaces. It is argued that the magnetic energy originally stored in the arc should be comparable to the kinetic energy of the moving filament.

The magnetic energy residing within a small cylindrical filament of diameter d, length ℓ, carrying a current I is:

$$\mathcal{E}_m = \frac{\mu_0 \ell I^2}{16\pi}. \tag{2}$$

If such a filament moves at constant velocity through a distance ℓ in time t its kinetic energy will be

$$\mathcal{E}_K = \tfrac{1}{2}Mv^2 = \frac{\pi\, d^2 \ell^3 \rho}{8t^2}, \tag{3}$$

where ρ is the density of the filament material. If the two energies are comparable then the bridging time is roughly:

$$t \sim \frac{\sqrt{2}\pi\, d\ell}{I} \cdot \sqrt{\frac{\rho}{\mu_0}} \tag{4}$$

If we assume the following as reasonable numbers:

$$\begin{aligned} I &= 1{,}000 \text{ amperes}, \\ \ell &= 3 \text{ mils}, \\ d &= 20 \text{ mils}, \\ \rho &= 10 \text{ gm/cm}^3, \end{aligned}$$

then equation (4) gives a transition time of 15×10^{-6} seconds. This figure is of the same order of magnitude as bridging times observed during experiments.

The rough model used here is only one stage more refined than purely dimensional analysis but seems to give reasonable agreement with experiments. Of importance is the design guide offered by equation (4). By means of proper choice of the welding circuit it is possible to select an arbitrary current versus time relationship. In order to avoid bridging effects, which are, of course, very erratic, the bridging time t should be maximized. By equation (4) the ratio of current to separation should, therefore, be minimized. Stated in words this means that if large currents are necessary for the process (this will be shown to be desirable in a later section) they should be confined to a period when the separation between the surfaces to be welded is quite large. The current should be sharply decreased as the surfaces approach each other.

DESIGN OF IDEAL WELDING CIRCUIT

In the previous section it has been shown that arc duration will vary over a wide range. This suggests that the system be designed in such a way as to be independent of arc duration.

The procedure will be to start with the desired temperature versus time relationship of the two opposing surfaces. From this the corresponding current versus time relationship can be found and finally the circuit giving such a current distribution selected. Obviously, the "safest" temperature-time relationship is one where the temperature is kept constant at the desired level T. The corresponding current distribution will be derived on the basis of one-dimensional heat flow. Let

u = temperature
T = desired temperature at surface
a^2 = diffusivity of material
x = distance in direction of heat flow
A = cross-sectional area over which heat flow occurs
K = heat conductivity of material
V_m = voltage across arc
i = transient current

Start with the differential equation for one-dimensional heat flow:

$$\frac{\partial u}{\partial t} = a^2 \frac{\partial^2 u}{\partial x^2}. \tag{5}$$

For the boundary conditions:

$$\begin{aligned} u &= 0 \qquad & t < 0 \\ u\,|_{x=0} &= T \qquad & t > 0 \end{aligned} \tag{6}$$

The solution is:

$$u = T\left(1 - \frac{2}{\sqrt{\pi}} \int_0^{x/2a\sqrt{t}} e^{-\beta^2}\, d\beta\right). \tag{7}$$

In order to determine the heat input required we must find the gradient at the surface. Expanding equation (7):

$$\frac{\partial u}{\partial x} = \frac{2T}{\sqrt{\pi}}\left[\frac{1}{2a\sqrt{t}} - \frac{x^2}{(2a\sqrt{t})^3} + \frac{x^4}{2!(2a\sqrt{t})^5}\cdots\right], \tag{8}$$

$$\left.\frac{\partial u}{\partial x}\right|_{x=0} = \frac{T}{a\sqrt{\pi t}}. \tag{9}$$

The required heat input must now be set equal to that supplied by the welding circuit:*

$$\tfrac{1}{2} i V_m = \frac{KAT}{a\sqrt{\pi t}}, \tag{10}$$

or

$$i = \frac{2KA}{aV_m\sqrt{\pi}}\,\frac{T}{\sqrt{t}}. \tag{11}$$

The current time relationship represented by equation (11) is that due to a capacitative transmission line working into a short circuit. Since the arc voltage is considerably lower than the voltage to which the line is charged, it is substantially a short circuit.

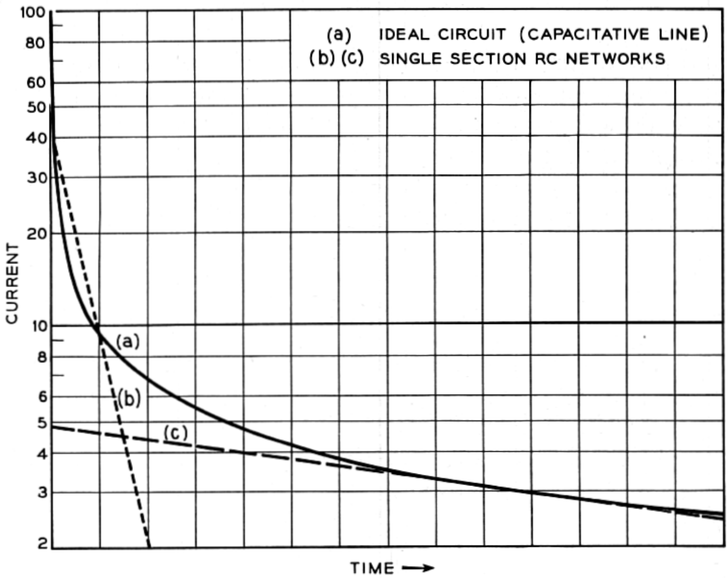


Fig. 3 — Current time characteristic. (a) Ideal circuit (capacitative line). (b) and (c) single section RC networks.

* It will be assumed that the energy of the arc is divided equally by the two opposing surfaces.

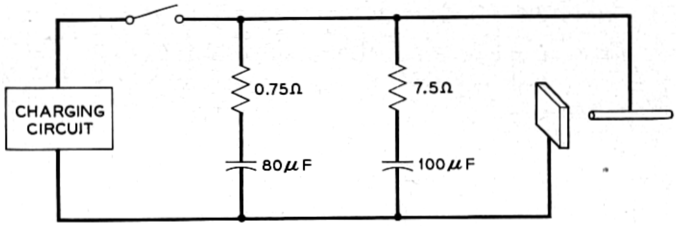


Fig. 4 — Practical welding circuit.

SELECTION OF A PRACTICAL CIRCUIT

It is probably not practical to use a distributed constant capacitative line having a current time relationship as plotted in Fig. 3. The line can, however, be approximated to the desired degree of accuracy by means of a series of r-c sections. The current discharge curve for a single r-c section plotted on the semilog graph of Fig. 2 will be a straight line. Clearly this is not a very good approximation of the ideal curve. If the constants are adjusted such that the desired initial high currents are met, the current will decay too fast allowing the surface to cool prematurely for long arc durations. If the constants are adjusted to match the desired curve for long arc times, the initial heating will be insufficient and short arc durations will produce poor welds.

A fairly good approximation of Fig. 2 can be obtained by as little as two r-c sections in parallel (Fig. 4).* Use of this circuit has resulted in considerable improvement not only in the uniformity of the welds obtained but curiously enough in the control of arc duration. The reason for the latter phenomenon is that with the multiple section circuit the desired bridging characteristics can be met much more closely.

THE MECHANICAL STRUCTURE

Relatively little is known about the effect of the mechanical design of the welding apparatus on the process. Basically, the mechanical constants of interest are the mass and velocity of the gun when the arc is being extinguished and the forces propelling the gun. The gun contains kinetic energy part of which is absorbed during the impact of the two parts to be welded. The remaining part will tend to produce rebounding of the gun. Clearly the weld must have cooled sufficiently when the gun draws back such that it can withstand the forces tending to pull it apart. The time allowed for cooling is then roughly one-half the period deter-

* The circuit configuration shown is equivalent to two L sections of a lumped constant line as usually depicted.

mined by the mass of the gun and the stiffness of the stationary part to be welded.

The effects on weld quality of that hammer blow produced by the gun are not well understood but there is some evidence that this blow may be advantageous in producing intimate mixing.

SUMMARY

The basic processes of percussive welding have been discussed. Large variations in arc duration are caused by the spread in the initiation separation, bridging phenomena, and the amplifying effect of evaporation.

The relative spread of initiation separation is minimized by working at high voltages, in excess of 1,000 volts. Bridging, which causes premature extinguishing of the arc, is minimized by maintaining the ratio of current to separation at a minimum.

A welding circuit offering independence from arc duration variations has been developed on the basis of one-dimensional heat flow. The analysis presented suggests a capacitative transmission line, which can however be approximated by two or more r-c sections. Greatly improved process control has been effected with this circuit.

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