An Arc Blow Simulator

Quantitative comparison of various arc deflecting magnetic fields is achieved by substituting mercury for the arc plasma and measuring the effects with a manometer

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ABSTRACT. Until now, studies of arc blow have employed motion pictures or gauss meters to obtain information. Neither technique, however, examines directly the forces acting upon a current-carrying fluid in a magnetic field that is at least partially self-induced. Now, however, by substituting mercury for an arc plasma as a current-carrying fluid, a technique has been devised to measure quantitatively, via a manometer, the magnitude and direction of the arc blow force on the current-carrying fluid. With this device, it is possible to simulate an enormous number of welding conditions, including multiple arc interactions, interactions with magnetic clamping devices, joint geometry effects and the like.

An arc blow simulator was constructed and data were obtained to show the effects of current magnitude and ground clamp location upon the arc blow force. Data for dc and ac arcs are presented.

Introduction

"Under certain conditions of arc welding, the arc has a tendency to distort out of shape or to be forcibly directed away from the point of welding, thereby making it difficult to produce a satisfactory weld. This phenomenon, called magnetic arc blow, is the result of magnetic disturbances that unbalance the symmetry of the self-induced field surrounding the welding arc." (Ref. 1). The average welding operator would probably use more graphic terminology to describe his experiences with arc blow.

Arc blow can be a nuisance or worse, causing undercut, porosity, cold laps and other defects. When it occurs, remedies like change of ground clamp location and wrapping welding cables around the workpiece are often employed on a more or less trial and error basis, though often past experience is helpful.

Studies of arc blow made in a systematic fashion, rather than trying to overcome a problem of the moment, are few. Mandel's Berg (Ref. 2) used high speed motion pictures of tandem GMAW arcs (ac, 120 deg out of phase) to observe attraction and repulsion effects on the arcs. When the two arcs were of like polarity, they were attracted to one another. When they were of opposite polarity, they repelled one another. Measurements were made of the fraction of time the arcs were deflected in various directions as a function of whether the lead electrode was electrically leading or trailing the trail electrode. This study was useful for optimizing phase sequence in tandem arc welding to obtain maximum welding speed.

Hicken and Jackson (Ref. 3) studied the effects of externally applied magnetic fields on GTAW arcs. They used an electromagnet to produce a field transverse to the welding direction and cause arc deflection forwards or backwards to obtain increased welding speeds. They measured the external field with a gauss meter and photographed the arc deflection and were thereby able to obtain quantitative data of arc deflection as a function of applied field strength.

Neither of the above studies, nor any other studies of which the authors are aware, were able to measure the forces acting upon a current-carrying fluid (arc) due to a magnetic field that is at least partially self-induced. What one is in general left with are a few rules of thumb for combatting arc blow. These are based upon experience and some knowledge of magnetic principles. For instance, it is well known that an arc tends to deflect away from any base metal geometry that tends to constrict the magnetic field in the base metal. Thus the arc deflects away from the ends of plates being welded together. Also, arc blow causes less problems when welding away from, rather than towards, ground. Arc blow becomes more severe at higher currents when the field is stronger. Arc blow is most severe in welding magnetic materials, especially those with a tendency to retain residual magnetism such as 9% nickel steel. And arc blow can become more severe when more than one arc is present. Means of minimizing arc blow effects include use of ac welding current, moving ground clamp location, and wrapping welding cables around the workpiece to set up a magnetic field to counter the field causing arc blow.

Conception of An Arc Blow Simulator

Arc blow results from a physical force caused by the interaction between a current conductor (the arc) and a magnetic field around the conductor which is at least partially self-induced. As an alternative to photographing the arc under various conditions to obtain data about arc blow, it would be desirable to measure the forces acting on the arc to cause it to deflect. Obviously,

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measuring forces in a plasma stream heated to 10,000 F is an extremely formidable proposition so that direct measurement may be considered impossible. However, if the temperature could be reduced greatly, the proposition becomes less formidable.

One way to reduce arc plasma temperature is to reduce the barometric pressure in the plasma and reduce the current density. However, Guile (Ref. 4) points out that low pressure, low current arcs do not obey the electrical motor laws obeyed by welding arcs and other conductors in a magnetic field.

The fact that welding arcs obey the same electrical motor laws obeyed by other conductors in a magnetic field was noted by the authors in considering the problem of measuring arc blow forces. This being the case, then another conducting medium could be substituted for an arc plasma and similar forces could be expected to act upon it if the current density in it were similar and the magnetic field around it were similar. An ideal conducting medium would be a liquid since then manometer measurements could be made of arc blow forces. Manometer measurements are convenient for measuring very small pressure differences as well as reasonably large ones. Mercury, being relatively inert, an electrical conductor and a liquid at room temperature, was selected as a workable substitute for an arc plasma.

Design of an Arc Blow Simulator

An arc blow simulator was designed and constructed to permit simulation of submerged arc welding conditions for reasonably heavy plate. The "welding electrode" was chosen to be a 3/8 in. diam copper rod. One end was connected to a welding power supply. The other end was screwed into a hollow bakelite cylinder. A second short copper rod was screwed into the other end of the bakelite cylinder. Two holes 180 deg apart and 1/16 in. in diameter were drilled into the void between the copper rods. These holes were connected to a manometer.

A 2 by 12 by 24 in. steel plate served as the simulated base metal. A 1 in. diam hole was drilled through the plate thickness centered 4 in. from one of the short ends of the plate. The plate was then slit by flame cutting from the hole to the near short end. The edge of the slit in the hole was welded shut with austenitic stainless steel filler metal, and an austenitic stainless steel plug was welded into the bottom of the hole. The hole was then filled nearly to the top with mercury.

The copper rod and bakelite cylinder assembly was then fixtured perpendicular to the plate with the short copper rod immersed in the mercury pool in the plate. The manometer and bakelite cylinder were filled with mercury. The mercury in the bakelite cylinder completed an electrical circuit from the long copper rod to the mercury in the chamber to the short copper rod to the mercury pool in the hole to the plate. Then the plate was connected to the ground of the welding power supply so that a simulated welding circuit was constructed. The long copper rod simulates the welding wire or rod, the mercury chamber simulates the arc, the mercury pool simulates the weld pool and the slit in the plate simulates the unwelded joint ahead of the arc which serves as a magnetic discontinuity to distort the field around the arc and help cause arc blow. Figure 1 shows a schematic of the arc blow simulator concept.

With the manometer inclined sharply to magnify displacement of the mercury by currents as high as 500 A, movement of the mercury in the manometer was over only a very short distance, on the order of a few millimeters, so that comparative measurements were difficult to make. To amplify the manometer displacement caused by arc blow forces, a hydraulic amplifier was conceived and constructed. This consisted of a mercury-water interface in a tube of much larger diameter than the diameter of the manometer tube. Then by inclining the water portion of the manometer at a 10:1 slope and having a 10:1 ratio between the inside diameters of the mercury-water interface and the water manometer tubes, a displacement magnification of approximately 60:1 could be obtained as compared to a vertical mercury manometer. The calculations and design details of the hydraulic amplifier are given in Reference 5.

Figure 2 shows an overall view of the arc blow simulator completely assembled with the hydraulic ampli-

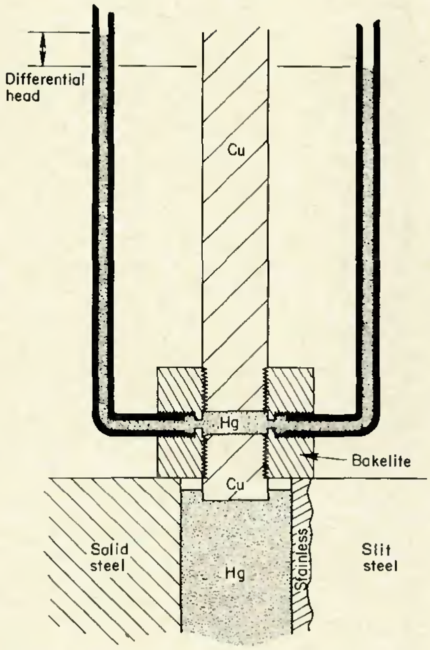

Fig. 1 — Schematic of the arc blow simulator

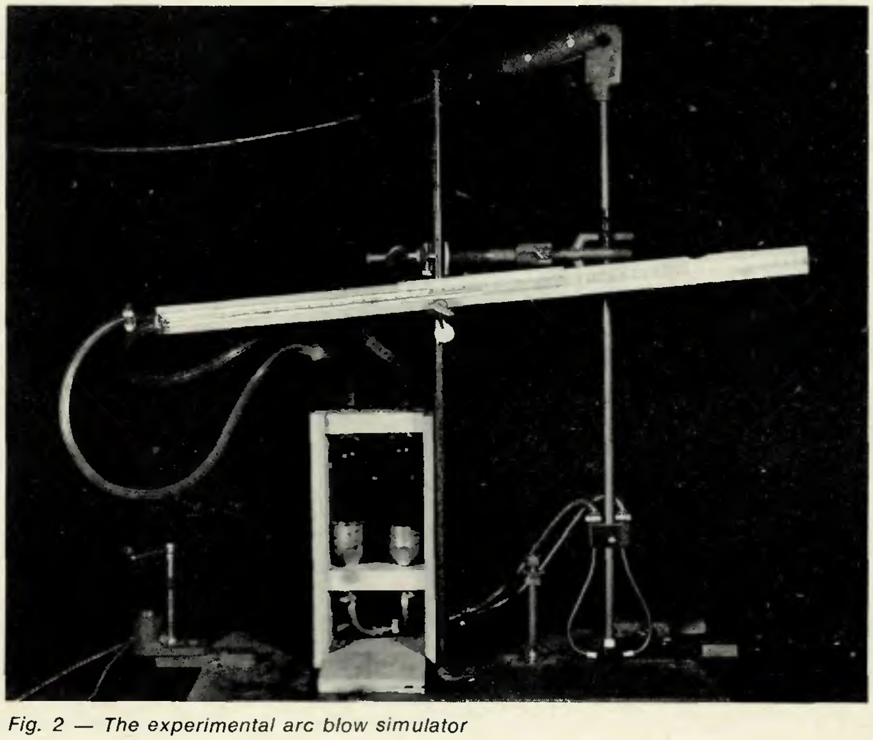

Fig. 2 — The experimental arc blow simulator

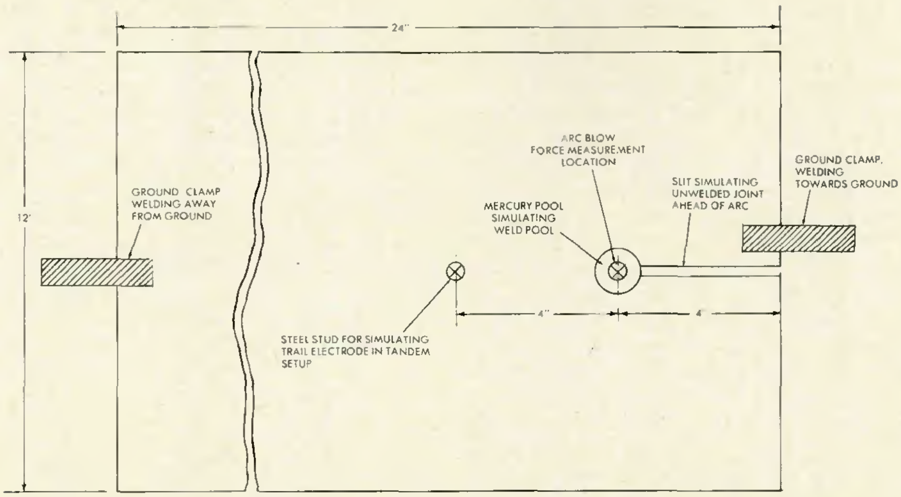

Fig. 3 — Schematic top view of arc blow simulator base plate. The simulated welding direction is always from left to right

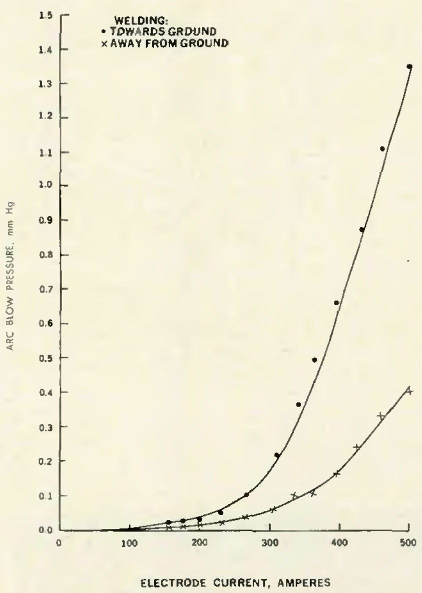

Fig. 4 — Arc blow pressure vs. electrode current for a single simulated dc arc. The force direction is always opposite to the direction of simulated welding

fier included. A second simulated arc could be included at any time simply by running current from a second welding power supply through a steel stud welded to the plate in line with the slit and manometer arrangement four inches away from the manometer. Then the effect of arc blow forces on the lead arc of a tandem arc welding setup could be examined.

Figure 3 shows a schematic top view of the base plate with simulated electrode and ground clamp locations. This will be useful for reference terminology later.

Experimental Procedure

Current for the simulated welding arc or arcs was provided by conventional welding power supplies — dc by rectifier machines and ac by transformers. In the case of dc welding, current measurements were obtained from the output of a 50 mV, 500 A current shunt connected to a strip chart dc recorder. In the case of ac welding, current measurements were obtained from the output of a toroidal current transformer connected to a strip chart ac recorder.

Measurement of the arc blow force was made by recording the water meniscus locations with current off and with current on. As can be seen in Figure 2, the manometer was attached to a meter stick readable to the nearest millimeter. Since the combination of inclining the manometer and employing the mercury-to-water hydraulic amplifier produced a 60:1 magnification, then the differential head across the simulated arc column in millimeters of mercury could be simply calculated by dividing the manometer readout by 60. So differential pressures as low as 1/60 mm Hg or 0.00032 psi could be measured.

It was noted that the current-off meniscus position tended to shift from its position when the arc blow simulator had not been used for awhile. This seems attributable to heating of the mercury due to its electrical resistance which results in expansion. When the current was switched on or off, from 3 to 10 seconds were required for the meniscus to come to rest, depending upon the amount of displacement of the meniscus — flow of the mercury through the arc blow simulator is constricted by the 1/16 in. diam manometer taps. So the procedure adopted in obtaining data was to read the current-off meniscus level, switch on the current and wait 10 seconds before reading the current-on meniscus level, switch off the current and wait 10 seconds before reading the current-off meniscus level, and repeat several times until three successive identical sets of current-on and current-off readings were obtained.

For a given set of simulated welding conditions, manometer measurements were made parallel and perpendicular to the slit in the plate which simulated the unwelded portion of a joint. In all cases considered, it was found that the force perpendicular to the slit was virtually zero so that the arc blow force direction was parallel to the slit. In the case of two dc arcs in tandem, force direction reversal could be obtained depending upon the relative polarity and magnitude of the two simulated arcs. But even in this case, no significant force perpendicular to the slit was ever noted. However more complex geometries could produce sideways forces.

Experimental Results

Curves of arc blow pressure as a function of current magnitude with a single electrode were developed for the conditions of welding towards ground and of welding away from ground. Direct currents of 150 to 500 A and alternating currents of 300 to 500 A rms were considered. Regardless of whether the simulated welding direction was towards ground or away from ground, the arc blow force was always opposite to the direction of simulated welding.

Figure 4 presents the force results for a single dc arc. It will be noted that the force for a given ground condition increases at a greater than linear rate as a function of current. It will also be noted that the force magnitude when welding towards ground is much greater at a given current level than the force magnitude at the same current when welding away from ground.

Figure 5 presents the force results for a single ac arc. In the case of ac welding away from ground, the force magnitude is too low at all current levels considered to determine the general shape of the curve. However when welding towards ground, the force magnitude again increases at a greater than linear rate as a function of current. The force magnitude is greater at a given rms current welding towards ground than it is at the same direct current welding away from ground and it is only slightly less than when dc welding towards ground.

Direct current tandem arc welding was investigated by applying a fixed current magnitude to the simulated trail electrode and measuring the arc blow force on the lead electrode as a function of lead electrode current. As noted previously, in simulated tandem arc welding, the force direction was always parallel to the slit in the plate (simulated groove). The force direction, however, could be made to reverse itself.

Figure 6 shows the arc blow pressure on the lead electrode as a function of lead electrode current for the conditions of no trail electrode current, 480 A trailing current of the same polarity, and 480 A trailing current of opposite polarity, all when welding towards ground. It will be noted that when the two electrodes have the same polarity, the arc blow force is greatly increased over that of the single electrode condition, and the force direction remains opposite to the direction of welding. But when the electrodes are of opposite polarity, the force on the lead "arc" reverses direction at low currents to the direction of welding. The force magnitude on the lead "arc" in this case stays at a relatively low level until at the highest current considered (700 A) the force reverts to the direction opposite to the direction of welding and the magnitude seems to be heading for large values.

Figure 7 shows the lead electrode arc blow pressure under conditions similar to those of Fig. 6, except that welding is away from ground. The results are qualitatively similar to those of Fig. 6 except that when the two "arcs" are of opposite polarity, the lead arc blow direction does not revert to the usual away-from-welding direction even at 700 A.

Some investigation of ac-dc tandem arc welding was also carried out. It was found that when the lead electrode is dc and the trail is ac, the force on the dc lead "arc" was not affected by the presence of the ac trail. When the lead "arc" is ac, the arc blow force is very slightly decreased by the addition of a dc trail.

Discussion of Results

One of the electric motor laws (Ampere's Law) states that the force acting on a conductor in a magnetic field is proportional to the product of the current in the conductor and the field strength perpendicular to the direction of the current and that the resulting force is perpendicular to both the current direction and the field direction. That is, the force is proportional to the vector cross product of the current and field. Since the field around the welding arc or simulated welding arc is largely produced by the current, then the field strength should be proportional to the current. This in turn implies that the force measured in the arc blow simulator should be proportional to the square of the current.

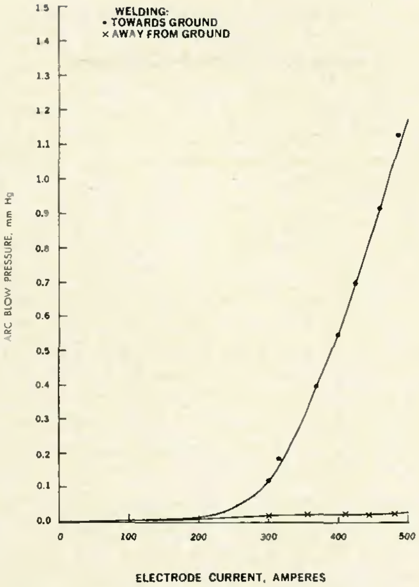

Fig. 5 — Arc blow pressure vs. electrode current for a single simulated ac arc. The force direction is always opposite to the direction of simulated welding

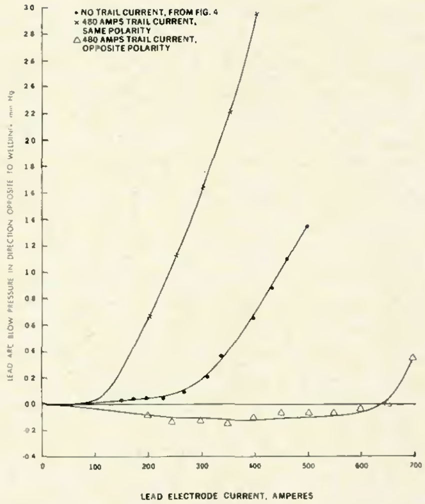

Fig. 6 — Arc blow pressure on lead arc vs. lead electrode current in simulated tandem dc arc welding towards ground

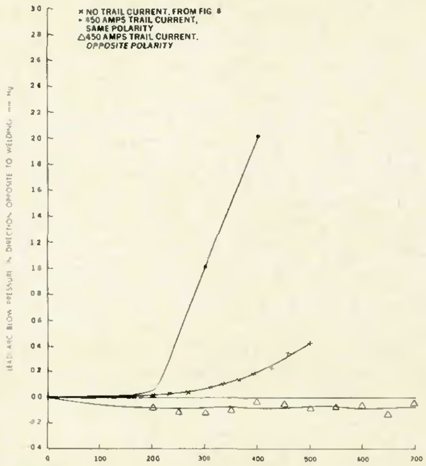

Fig. 7 — Arc blow pressure on lead arc vs. lead electrode current in simulated tandem dc arc welding away from ground

A Gauss meter was used to measure the field strength around the simulated base metal plate both above and below the plate in the vicinity of the simulated arc. In all cases, the field strength at any given point was indeed found to be a linear function of the current in the arc blow simulator. So each of the curves in Fig. 4 and 5 could be expected to be represented by an equation:

$$\Delta P = KI^2$$

where ΔP is the differential pressure in the arc blow simulator, I is the current and K is a constant of proportionality for the particular current type (dc or ac) and ground location.

Log-log plots of the data in Figs. 4 and 5 were made which indicated that the data better fit curves of the form:

$$\Delta P = KI^n$$

where n was between 3.0 and 4.0 instead of the expected 2.0. This seemed to apply to both dc curves and to the ac towards ground curve. The ac away from ground force magnitudes were considered to be too low to get a usable estimate of n. The method of least squares was then used to estimate n for the data of Figs. 4 and 5. This resulted in the following best estimates of n:

DC towards ground, n = 3.36
DC away from ground, n = 2.88
AC towards ground, n = 3.80

This fairly pronounced deviation from the expected force or pressure proportionality to I^2 is of uncertain origin. Several hypotheses might be offered. The observation that the field strength around the plate varies linearly with current does not necessarily mean that the field strength within the arc column (mercury chamber) varies linearly with current. The current in the base plate may constrict locally where it enters the plate from the electrode, and the constricting tendency may increase with increasing current so that the field strength in the simulated or real arc column may not be a linear function of current. The field in the simulated arc column could not be sampled with the Gauss meter.

Another possibility is that the current density may not be uniform across the simulated arc column, thereby distorting the current-field interaction. Other hypotheses could no doubt be proposed as well.

The observation that the arc blow force is considerably reduced under the simulated welding-away-from-ground condition as compared to the welding towards ground condition (Fig. 4) agrees with the normal qualitative observations of welding engineers.

At first glance, it may seem impossible that there should be a net average arc blow force under ac welding conditions. However, it must be remembered that since the field is produced by the current, when the current reverses direction, so does the field. The resulting vector cross product of the current and field does not reverse direction, therefore, and a non-zero net average force results. The observation of a markedly lower arc blow force when ac welding away from ground than under any other condition agrees with the normal qualitative observations of welding engineers.

The increase in arc blow force on the lead arc when dc tandem arc welding with electrodes of like polarity also agrees with the normal qualitative observations of welding engineers. It is also to be expected since the electric motor laws indicate attraction forces between parallel currents flowing in the same direction, so that the attractive force between the two currents adds to the force acting opposite to the direction of welding.

When dc tandem arc welding with electrodes of opposite polarity, the force between parallel currents flowing in opposite directions is one of repulsion so that this force tends to push the lead "arc" in the direction of welding. But the interaction between the lead "arc" and the field due to its own current in the plate tends to push the lead "arc" in the direction opposite to that of welding. In this case the two forces try to cancel one another out. As the lead electrode current is increased, the magnitude of both forces increases so that the net effect on the lead arc could be expected not to vary much until the two currents are of markedly different magnitudes so that one force or the other becomes dominant. The arc blow simulator does behave this way.

In interpreting the results obtained with the arc blow simulator, it should be remembered that the measurement being made is force or pressure. Thus while high current arcs may feel a greater pressure than lower current arcs, the higher current arcs also seem to have a certain "stiffness" which resists deflection. This stiffness tends to direct the arc in line with the electrode even if this is not the direction of the shortest line from the electrode tip to the base metal. This stiffness effect can be most readily noted in GMA welding when the metal transfer mode changes from globular to spray with increasing current.

Conclusions

A fairly simple prototype device, which allows quantitative measurements of arc blow forces to be made, has been constructed, and data which generally agrees with qualitative observations on welding arcs has been obtained with it. The arc blow simulator permits quantitative comparison of the forces tending to cause magnetic arc blow under a wide variety of welding conditions. It is believed that this device can be of significant value to welding engineers in finding means of combating arc blow and to scientists in studying the arc blow phenomenon.

Acknowledgments

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