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Observations of Exploding Droplets in Pulsed-Arc GMA Welding

A laser photographic technique reveals some droplets explode, causing spatter, as the drop is pinched off from a non-cored steel wire. Holography can also be usefully applied to the study of this process.

BY M. B. C. QUIGLEY AND J. M. WEBSTER

ABSTRACT. A new photographic technique used to investigate pulsed-arc GMA welding has shown that as droplets from conventional non-cored steel wire are rapidly accelerated to the workpiece they frequently explode, causing spatter. The techniques of high speed photography with laser shadowgraph and holography are described and some typical records are shown and discussed.

Introduction

In GMA gas metal-arc welding a consumable electrode is melted by an arc between itself and the workpiece. Shielding is obtained from an externally supplied gas or gas mixture via a nozzle around the electrode; the gas protects the weld pool from contamination. Metal is transferred from the melting consumable electrode in a number of ways depending upon electromagnetic, gas flow and gravitational forces.

One of the major problems of GMA welding is that of spatter. Spatter can be formed at any point between the wire electrode and the workpiece; figures of up to a few per cent have been quoted for some processes. To understand the mechanisms involved in normal metal transfer and in the formation of spatter, we have used high speed photography and holography.

The extreme luminance of the welding arc masks photographic studies of the process of droplet formation and transfer. Previous photographic investigations of welding processes have usually relied upon arc lamps of up to 20 kW to provide a backing light for shadowgraph photography; however, even this is not always sufficient to overcome completely the intense radiation from the welding arc.

This paper describes how a new laser technique employing a continuous wave laser with an output of 20 mW can be applied to GMA welding arcs. In particular it illustrates detail of the formation of droplets at the consumable electrode tip where the highest intensity of visible radiation from the arc exists.

Early experiments in holographic techniques have indicated that it is possible to reconstruct a fully three dimensional picture of the complete process taken at any one moment in time. From such optical, three dimensional reconstructions it is simple to determine the size, mass and location of any object within the field of view. It is therefore possible to determine the directions and velocities of spattered particles from successive pictures.

Using these techniques, visualization of drop transfer has been simplified. In particular it has been found that some droplets from non-cored steel wire blow up like a bubble and explode, causing spatter. Values of spatter from a pulsed-arc GMA set of about 3.5% have been recorded.

Importance of GMA Welding

The Central Electricity Generating Board's welding requirements are largely for thick material (up to 150 mm), large diameters (up to 2m) and awkward geometries such as tube-to-tube plates. The thickness requirements demand high current and high metal deposition rates. GMA welding (or its "second cousin" submerged arc welding) is the best system at present in use from this point of view, but it suffers from various problems. One of these is the difficulty in setting up a GMA set for any particular applica-

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tion. At present sets either have variables of "slope (V/I) and voltage" or "voltage and inductance" apart from the normal variables of current and wire feed rate.

The problem of variations from one type of equipment to another is one which besets welders in the field and can cause varying qualities of weld and possible failures. This problem, together with the complexity of the various controls, makes skilled GMA welders extremely rare. It causes many welds to be done by the slow (and frequently ineffective) stick technique, since that requires less skilled personnel.

It is often necessary to use particular gases, for example CO_2 or mixtures of gases, as the shielding medium. Apart from its slightly oxidizing nature which increases with temperature as the gas dissociates, carbon dioxide would appear to be attractive as it is inexpensive and in plentiful supply. However, the manner in which droplets of metal are detached from the electrode in an atmosphere of CO_2 differs markedly from that in argon for the same welding conditions; whereas in argon, spray transfer is achieved at fairly low currents, spray transfer is only achieved in CO_2 at very high currents. The composition of the shielding medium also has considerable economic significance; for example, if electrode costs are £ 0.27 per kg (30¢ per lb) and labor costs are £0.22 per kg (24¢ per lb) for reasonable operating factors and metal deposition rates, by comparison the cost of CO_2 is between £0.019 and £0.08 per kg (2 and 8¢ per lb) whereas Argoshield 5 (5% CO_2) costs between £0.21 and £0.86 per kg (23 and 94¢ per lb).

While various gas mixtures appear to work well for the purpose for which they were developed, the reasons for employing any particular mixture seem to have been arrived at empirically and are not necessarily fully understood scientifically.

If some understanding can be obtained concerning the mechanisms involved in metal transfer in the GMA process and the physical significance of the small changes in gas composition, then it is to be hoped that the process can be made simpler and hence have very much wider application. It would also be hoped that some savings can be made in the cost of the shielding gases.

Experimental Procedure

A B.O.C. MRCS 200B welding rectifier set, in conjunction with a PWI pulsed welding unit operating at 100 pulses per second, was the power source. This unit pulses the current from a value sufficient to melt the wire slowly to a level at which the wire would normally be transferred as a stream of small droplets. The pulsing rate is such that, in general, only one droplet is transferred per pulse.

The current, wire feed speed and inductance were adjusted to give smooth, relatively spatter-free metal transfer via a fixed torch to a moving workpiece. A Tektronix 555 oscilloscope was set up with a probe to monitor the potential at the contact tip relative to the workpiece.

The shielding gas used was Argoshield 5 with a flow rate of 0.4 l/s (50 ft^3/hr) and the wire speed was found to be approximately 130 mm/sec.

Photographic Techniques

Equipment

For the cinematographic recordings a high speed, 16 mm "Hitachi" 16-mm camera was used. This camera is capable of framing speeds up to 10,000 pictures per second; the actual framing speed was calculated from a 1 kHz pulse mark recorded on the film edge.

Laser Transmission Techniques

Traditionally the external light source used to overcome the intense visible radiation from the welding arc has comprised a high power xenon or carbon arc lamp. While this is certainly sufficient to enable the flow of molten metal in the welding pool to be studied, its power is usually insufficient to permit detailed study of the electrode arc root region where the metal droplet is formed. In pulsed-arc welding the luminosity is greatest at the moment of detachment and usually fogs the film.

Application of monochromatic light to the photography of events occurring within an intense electric arc offers considerable advantage over conventional thermal or other discharge polychromatic sources. Parameters affecting the use of such techniques have been considered in detail elsewhere (Webster & Siddons, 1969). However, points particularly relevant to this experiment can be briefly summarized as follows:

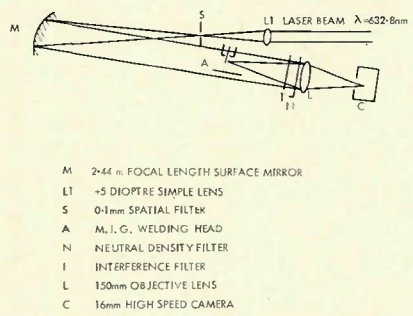


Fig. 1—Optical system for laser shadowgraph technique

A laser is a convenient source of highly directional quasimonochromatic light. Its highly directional properties enable the optical geometry of the photographic system to be designed to use almost all the energy emitted by the laser. Thus typically at a wavelength $\lambda = 632.8$ nm, 20 mW provides sufficient illumination for shadowgraph high speed photography at 10,000 pictures per second.

Providing the emission wavelength of the laser does not coincide with a prominent emission from the welding arc, the light source will be transmitted freely through the arc. Thus, by interposing a narrow band transmission filter (matched to transmit the laser light) in the analysing beam between the arc and the camera, almost all of the arc light will be removed. Providing the output power of the laser is sufficiently high, any arc continuum transmitted by the filter can be reduced to below the sensitivity threshold of the film by placing neutral density filters over the camera objective lens.

In our experiments this technique has been extensively employed to obtain cine shadowgraph and holographic results. It has enabled us to record visually the liquid metal droplets being formed and released from the electrode tip, the region normally shrouded in the intense welding arc.

Shadowgraphs

Figure 1 illustrates the optical layout used to obtain shadowgraphs. Illumination is provided by a Ferranti 25 mW helium-neon laser working in the TEM_{00} mode. The emergent laser beam is approximately 2 mm diameter and has a Gaussian distribution of energy across it. To enable the center of the beam to cover the entire region of interest, therefore ensuring an evenly exposed negative, the beam was expanded by employing a +5 diopter thin lens. At the point of focus of the condenser lens a 0.1 mm diameter aperture was located to act as a spatial filter to clean up the laser beam optically. A 210 mm diameter, 2.52 m focal length mirror lens was located at its focal length from the spatial filter and effectively produced a parallel beam of light; a mirror lens was chosen for this work because its long focal length enabled the optics to be kept well clear of the welding equipment.

The camera lens was a 150 mm, f2.8 objective operated at maximum aperture and focused upon the welding electrode tip. An interference filter, transmission peak $\lambda = 632.8$

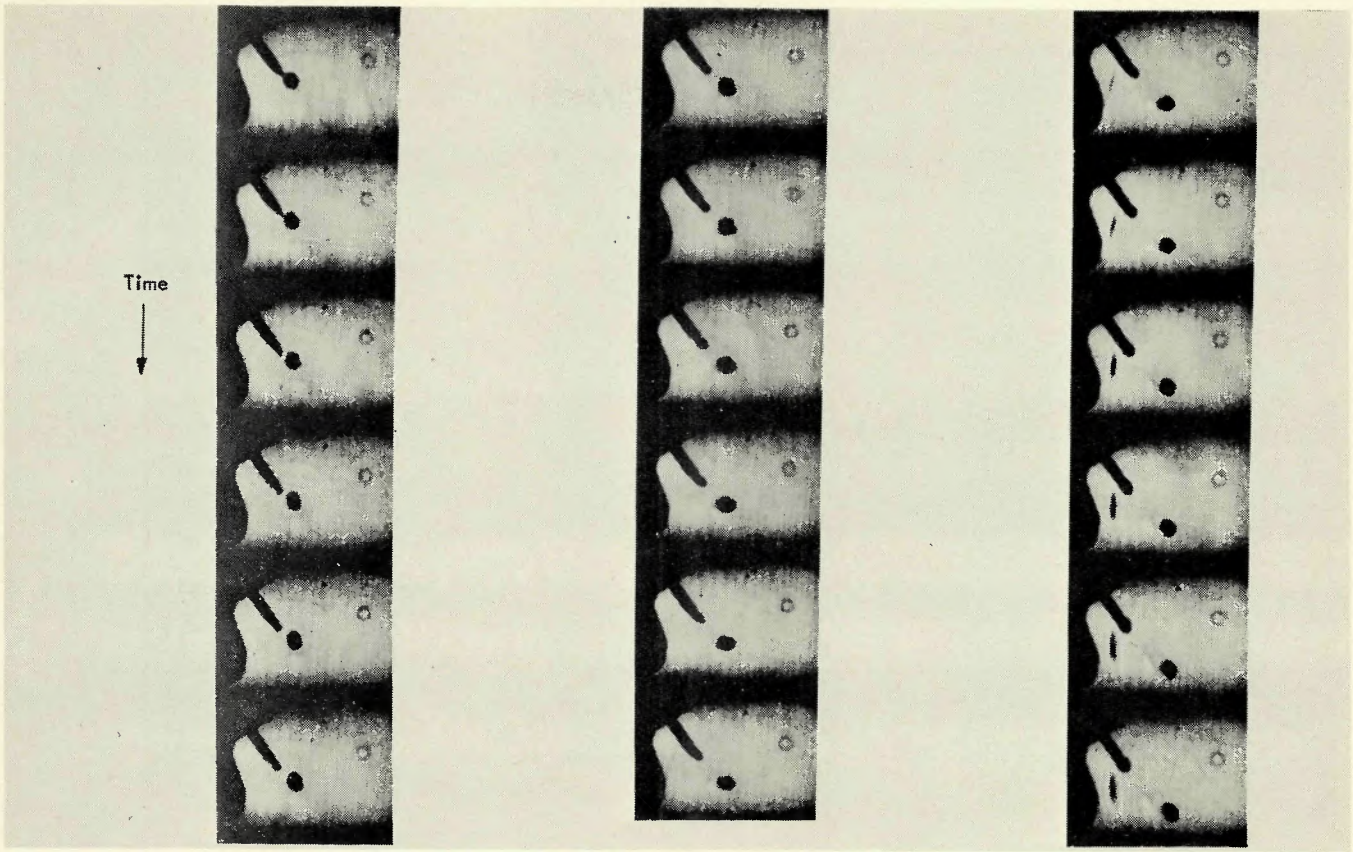


Fig. 2—Normal or smooth transfer mode for weld metal droplets

nm and half peak band width 2 nm, located in the beam between the camera and the arc, removed the majority of the arc luminance. Neutral density filters to the value ND 2.0 were located with the interference filter and reduced both the laser energy and the arc continuum to an acceptable minimum for recording on the film.

Holography

Conventional photography is a recording of a focused image of the subject represented in terms of tones. Holography (Smith 1968), differs from photography in that it is a recording of the light wave front emanating from the subject at the time of exposure. In the case of these experiments this was accomplished by the creation of an interference pattern on the recording film by coherent laser light wave front diffracted by the subject, representing the signal, and the use of an undisturbed reference beam.

To reconstruct the holographic image the processed plate or film is placed in a beam of coherent light of similar wavelength. The interference fringe pattern, which is a recording of the original wave front diffracted by the subject, selectively diffracts and reconstructs an image of the original subject fully in three dimensions.

The reconstructed image may be optically examined in much the same way as if the original subject had been frozen in time and space. Measurements relating to size and location in three dimensional space can easily be made. In particular it becomes possible to follow spattered metal falling outside the weld bead region.

A Barr and Stroud L.U.6. pulsed ruby laser was employed as the coherent light source for making the holograms. Operated in the "Q" spoilt mode this equipment will produce a single pulse of light of typical duration 20 ns and bandwidth less than 0.001 nm at a wavelength of 694.3 nm.

As with the laser shadowgraph technique, a narrow band interference filter was used; it was matched to transmit the laser light but to eliminate the arc luminance.

Results and Discussions

Shadowgraph

The laser shadowgraph experiments demonstrate the various modes by which metal transfer is achieved in a pulsed-arc system. In the normal manner in which the process is intended to function (designated Type 1) a single droplet is transferred smoothly to the workpiece on each pulse. This is shown in Fig. 2. In this case it was found that a sudden acceleration of up to 300 g occurred very shortly after detachment (0.3 to 0.5 ms).

Various alternative modes of metal droplet transfer were found; of particular interest were two related types, called 2a and 2b, where large bubbles were formed, generally in the stage between necking and detachment. The bubbles usually exploded; in case 2a into multiple droplets which then constituted spatter at the workpiece and in type 2b where the remnants of the exploded bubble coalesced into only one droplet which was then transferred relatively normally to the workpiece. These are shown in Fig. 3 and 4 respectively.

A count was taken from the high speed film records of about 250 droplets under typical welding conditions. The result: (a) 73% normal drop transfer, which usually included a small puff of gas; (b) 15% blew up but reformed into a normal droplet; (c) 12% blew up and exploded into smaller droplets.

Approximately 70% of the exploded material appeared to reach the weld pool so that the photographic evidence suggests that about 3.5% of the total material constituted spatter. This is of the same order as spatter measured on plates in the form of cold, loose metal droplets.

Milner (1970) has seen similar explosions in conventional spray transfer GMA welding but only near the weld

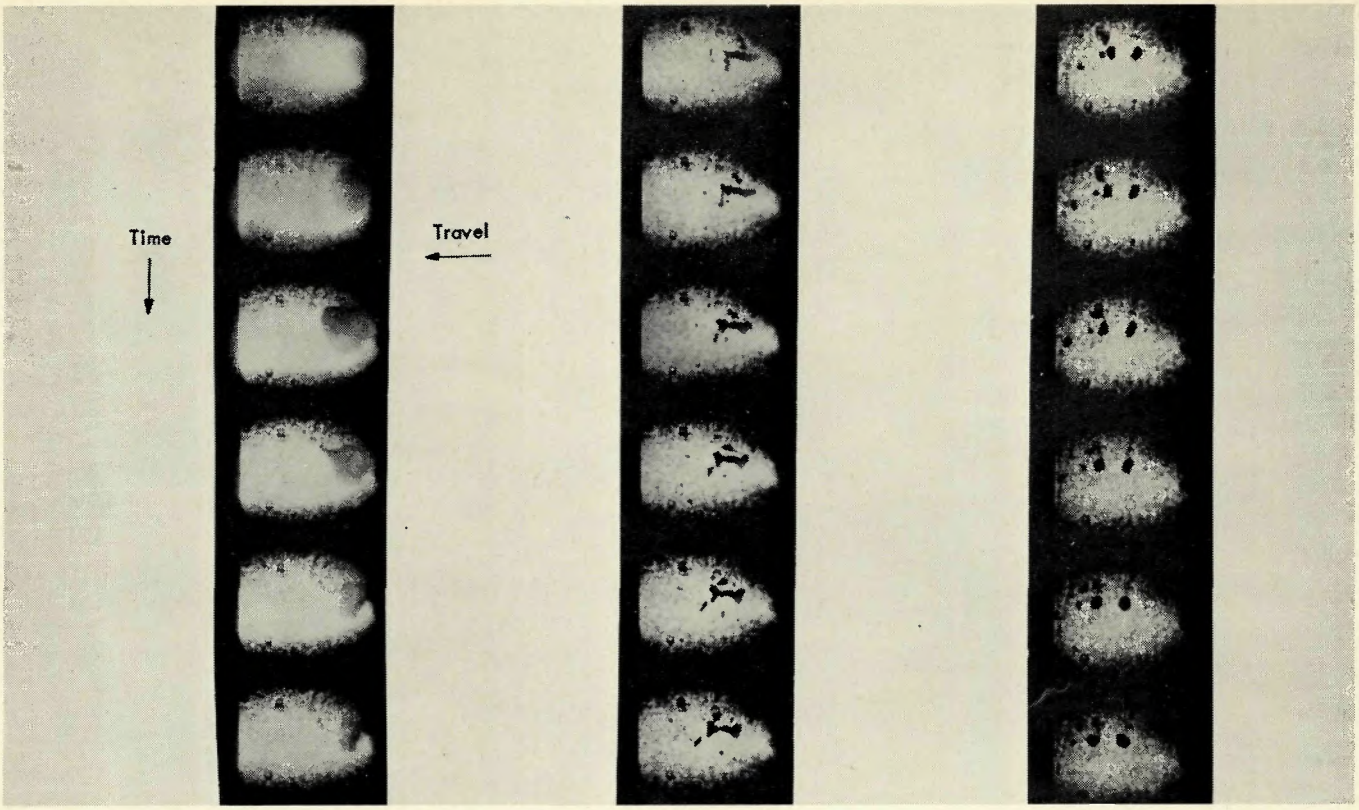


Fig. 3—Explosion of bubble droplet into fragments

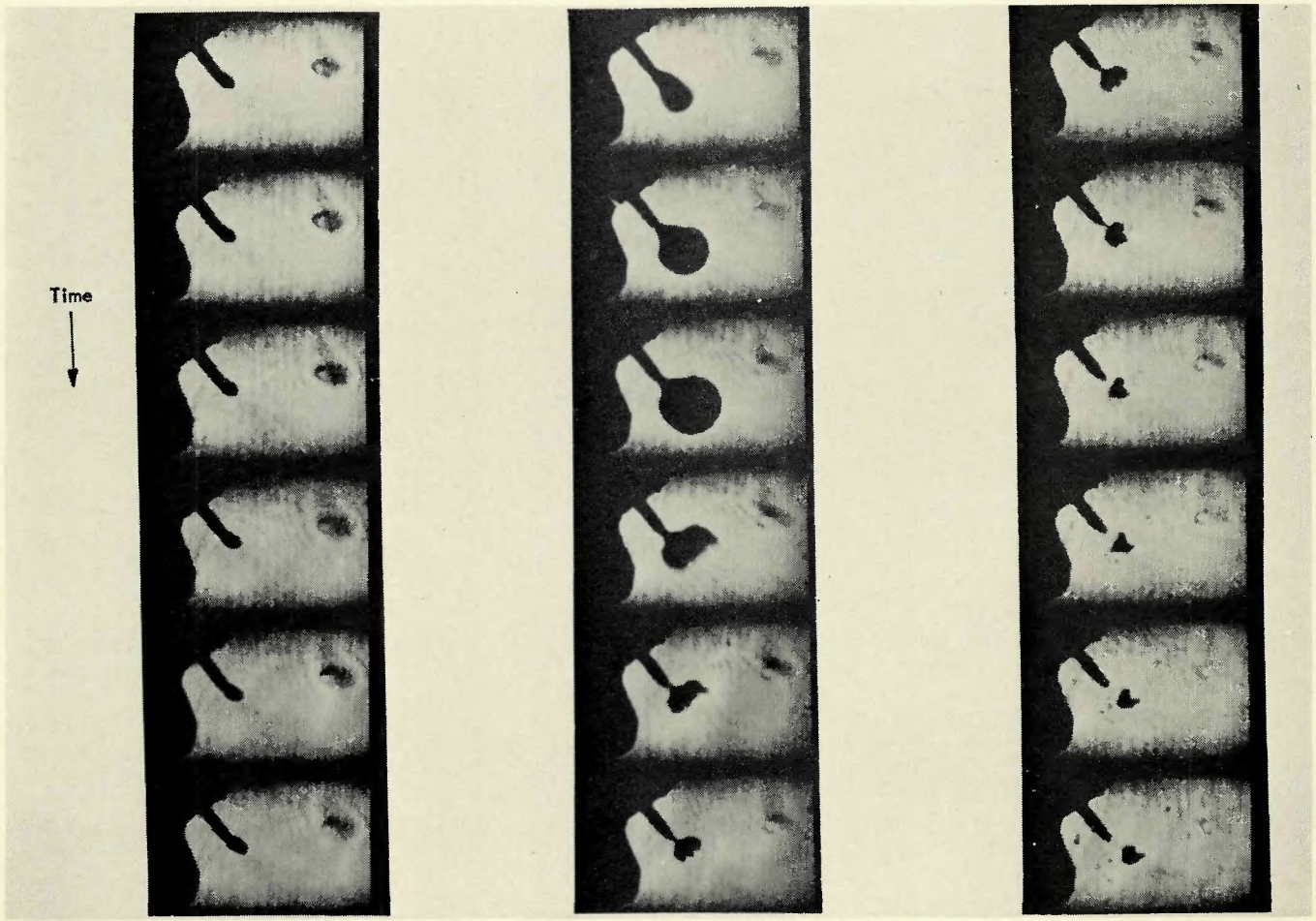


Fig. 4—Explosion followed by coalescence

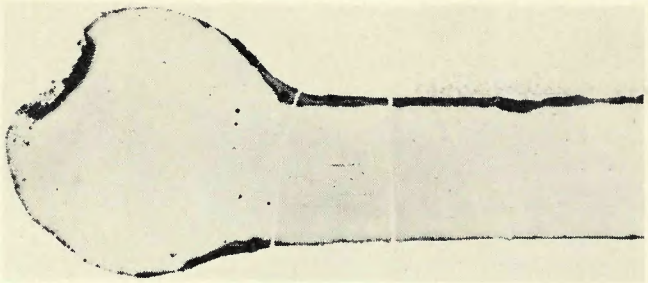


Fig. 5—Photomicrograph of inclusions in consumable electrode wire

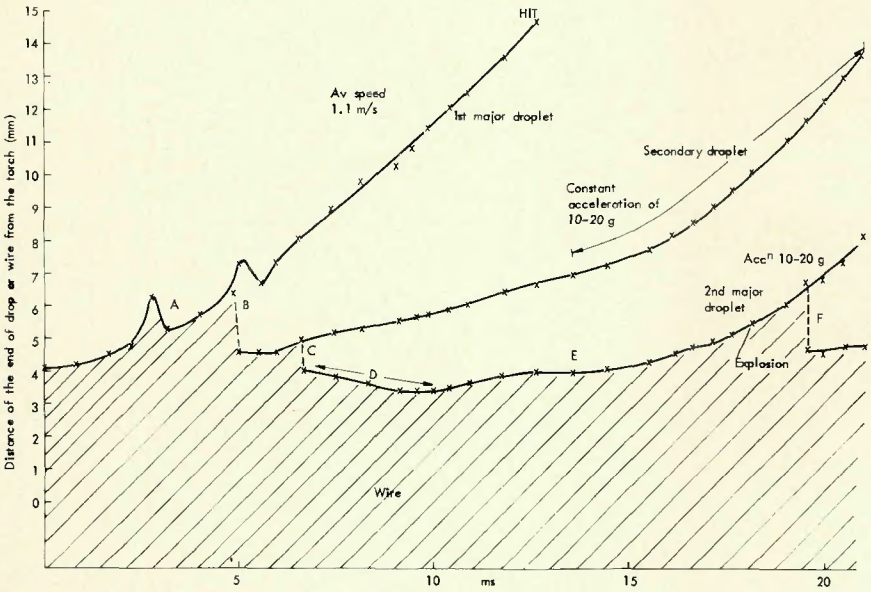
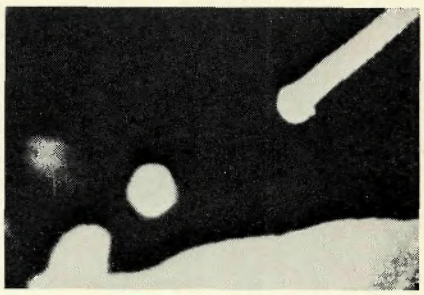
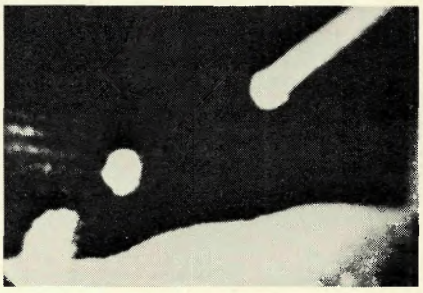


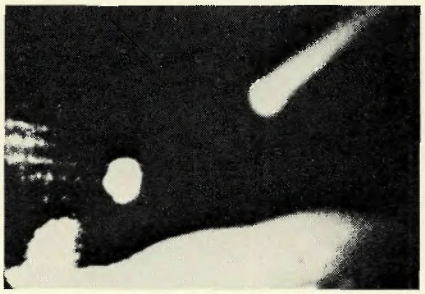
Fig. 6—Various accelerations of droplets when torch is horizontal



Focus plane on electrode



Focus plane on droplet



Focus plane on solidifying drop

Fig. 7—Reconstructed hologram of metal transfer in a pulsed GMA welding arc. Laser $\lambda = 694.3$ nm; duration = 20 ns; welding rod 45 deg to optical axis. Mag: 8X

pool and the bubbles are obviously caused by some heating process.

In pulsed-arc welding the droplets are heated more rapidly and so reach higher temperatures. This would cause the explosions earlier in our case than in the case of conventional GMA welding.

Figure 5 is a photomicrograph of a sample of the mild steel wire used in these experiments, and it clearly shows inclusions in the metal. Particularly at the very high temperatures involved in pulsed-arc GMA welding the inclusions will melt and be dissociated and CO may be formed.

This wire, although not especially pure, was standard wire used by the C.E.G.B. in a variety of welding operations. In case the bubbles only appeared with a faulty batch of wire, the experiments were repeated with other batches of wire and over a range of welding conditions. Similar results were obtained.

At first sight such bubbles are undesirable since they certainly produce spatter and may indicate gas or inclusions in the weld itself. However, we have no direct metallurgical evidence of faulty welds and, as a pure speculation, it might even be worth considering the possibility of encouraging such explosions, since less gaseous or volatile material might then result in the weld. Variation of the welding circuit parameters (to change droplet heating rates and transfer processes) might be expected to produce such an effect.

Another mode of transfer (types 3a and 3b), concerns situations where a secondary, and smaller, droplet follows the major droplet. Type 3a is when the torch is approximately vertical and type 3b represents the situation when the torch is horizontal. For type 3b a graph (Fig. 6) has been drawn showing the position of the end of the wire and/or the end of the droplets as a function of time; various interesting features can be pinpointed. At time A a small bubble occurred followed by another at B. Also at about time B this first major droplet detached; this was followed at C by the small secondary droplet. During time period D the major and secondary droplets had approximately constant speeds and the molten wire tip was retracting due to surface tension forces. At this time the current was at the low level. At around point E the increase in current occurred and the speed of the wire tip increased, apparently accelerating at 10 to 20 g as the tip became more fluid and began to pinch.

At point F this second major droplet detached. However, between E and F the small secondary droplet was also accelerated at about 10 to 20 g, although long since disconnected from the wire tip. It had been poised, almost stationary (only about 0.3 m/s) in the gap until the next current pulse occurred at which point it accelerated sharply towards the workpiece. This

effect appears to be due to plasma streaming (Ludwig, 1959) which occurs in situations where there is a rapidly changing cross section. These GMA welding arcs show a divergence in cross section; when this occurs, the magnetic field strength, the current density and the pressure in the axial direction all decrease; hence gas flows away from a narrow region, in this case away from the electrode and towards the workpiece.

The force needed to produce such an acceleration on a droplet a millimeter or so in diameter is around a millinewton. Accelerations up to 300 g (3 km/s^2) have been observed in some cases, calling for forces of 10 millinewtons or more which are comparable with that mentioned by Ludwig (1959). Such drag forces call for streaming velocities of a few hundred meters per second, a fraction of the speed of sound in the hot arc gases. These velocities are consistent with our photographic evidence and those quoted by Ludwig (1959).

Holography

Figure 7 illustrates a hologram of a typical transfer of two droplets into the weld pool and the formation of a third. The welding torch was set up at approximately 45 deg to the optical axis. At the reconstruction stage the plane of focus of the camera has been varied to obtain a sharp image of: A, the electrode tip; B, a droplet in flight; and C, the droplet coalescing into the liquid weld pool. By employing this technique it is simple to ascertain, with all three dimensions visible, the size, mass and location of any object in the field of view, over a very large depth of focus, greater than can be obtained with conventional techniques.

Conclusions

A laser photographic technique that has not previously been used for the study of the metal transfer process in the GMA welding arc has been described. Preliminary results using a pulsed-arc set and non-cored steel wire have shown that some droplets explode, causing spatter, as the droplet is pinched off from the wire. It has also been shown that holography can be usefully applied to the study of the process.

Acknowledgement

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"Review of Service Experience and Test Data on Openings in Pressure Vessels with Non-Integral Reinforcing"

by E. E. Rodabaugh

During the past ten years an extensive test program on nozzles and openings with integral reinforcing has been carried out under the guidance of the Pressure Vessel Research Committee of the Welding Research Council. Integral reinforcing is defined as reinforcing which is fully continuous with the shell; as contrasted to pad or saddle reinforcements, which are welded to the shells at the inner and outer peripheries. The ASME Nuclear Vessels Code requires that reinforcing be integral; the test program was intended to provide design data for such integrally reinforced openings. The results of this test program is now reflected in the ASME Nuclear Vessels Code in the form of stress indices and work is underway to more generally revise ASME Code rules for design of integrally reinforced openings.

However, many and perhaps most openings in pressure vessels are reinforced with pads or saddles; i.e. nonintegral reinforcing. The purpose of this report is to review available data on nonintegrally reinforced openings as perhaps a first step towards improvement ni code design rules for such reinforcing.