

## KEYNOTE ADDRESS AN ICONOCLAST'S VIEW OF THE PHYSICS OF WELDING—RETHINKING OLD IDEAS

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### An Iconoclast's View of the Physics of Welding - Rethinking Old Ideas

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#### ABSTRACT

Many of the physical explanations of welding processes were proposed initially as hypotheses which have never been tested either experimentally or theoretically. Although some of these hypotheses are no doubt correct, a number are not correct and cannot stand up to more detailed analysis. It is necessary to review these ideas from time to time to test their veracity. Otherwise, the progress of welding science can become limited due to reliance on incorrect principles.

#### INTRODUCTION

Due to its great commercial importance, the practice of welding has advanced much farther than has the science of welding. As engineers have discovered phenomena important to the practice of welding, they have offered hypotheses about the process which have been accepted without subsequent proof. Over time, these hypotheses have come to be regarded as established facts, some of which are accurate and some of which are not. As one studies the field of welding, or any field for that matter, it is essential that our fundamental understanding be based upon *proven* facts rather than speculative hypotheses. In this paper I will attempt to examine some widely held hypotheses concerning welding processes, which have come to be regarded over time as facts. It will be seen that many of these hypotheses, although seemingly reasonable and logical in concept, cannot stand up to quantitative analysis. As one sage put it:

"It is not what I don't know that hurts me.  
It is what I know, that is not true, that hurts  
me."

The progress of human knowledge in welding, as in all fields, requires an iconoclastic view of things as we know them - not for the sake of ridiculing what has gone before - but for the sake of correcting former errors which limit our future progression.

For purposes of this presentation, I have chosen several of the topics from a recently published reference on welding [Lancaster, 1986]. This text provides a compilation of the current knowledge of welding physics as accepted by many of the leading practitioners in the field. While the bulk of this text is very accurate and represents a useful contribution to the field of welding, one will see that even in a work of this stature, many tentative hypotheses are presented as reputable fact.

#### 1. THE TEMPERATURE OF WELDING ARCS

If asked to develop a sensor to control the arc welding process, a physicist will quickly decide that one can use spectroscopy to measure the temperature of the arc. While this is in fact true, the fatal flaw in this reasoning is the assumption that the temperature of the welding arc has a primary effect on the process - it does not.

It seems reasonable to those uninitiated in welding science to assume that it is the heat of the arc plasma that melts the metal being welded. This is roughly 20 percent correct. Cobine and Burger [1955] pointed out that the bulk of the heat to the anode from an electric arc, is due to the flow of current into the metal. Later, Quigley et al. [1973] quantified and extended Cobine and Burger's work to show that 80% of the heat is carried by the electric current and only 20% by conduction from the hot gases. Nonetheless, many people still concern themselves with measurement of the temperature of welding arcs.

One of the first things to be done in estimating the temperature of a welding arc is to investigate the ionization of argon. This ionization as a function of temperature is given quite accurately by the Saha equation and numerous plots of argon ionization versus temperature have been generated [Lancaster, 1986, p. 13-18; *Welding Handbook*, 1987, p. 44].

Some people like to assume that the welding arc is fully ionized for this makes further calculations more simple. In such a case, the minimum temperature in argon as predicted by the Saha equation is more than 20,000 K. This assumption is incorrect. Using the fact that the electron mobility in an atmospheric pressure welding arc is roughly 100 times as great as the ion mobility and given the value of electron mobility as measured by Schoeck [1963], one can easily estimate that the degree of ionization of the welding arc need only be 5 to 30% in order to conduct the welding current. By applying Steenbeck's Minimum Principal [Hoyaux, 1968] thermodynamic arguments or simple logic, one can conclude that the arc will seek the lowest possible temperature for which sufficient electrons are available to carry the welding current.

One problem in assuming that one should look at the ionization of argon in order to determine the temperature of the arc is that metal vapors are also present. Glickstein [1982] and Dunn and Eagar [1986] showed that even small additions of metal vapors to the inert gas plasma will perturb the thermal-electrical properties of the plasma. The result is that the measured arc temperatures on real weld pools containing metal vapors are often much less than those on water cooled copper anodes using pure argon [Glickstein, 1976], although considerable discrepancy still exists in these measurements. [Lancaster, 1986, p. 185-192]. Fortunately, it does not make any difference to those interested in heat transfer to the workpiece during welding. The primary concern in welding should be the distribution of current across the surface of the anode, for this is the primary factor controlling heat input into the workpiece. Unfortunately, such measurements can only be made on water cooled copper baseplates in which no metal vapors are present in the plasma. [Tsai and Eagar, 1985]

## 2. HEAT TRANSFER USING VARIOUS SHIELDING GASES

It is well known that one will melt more metal with a 100 ampere helium arc than with a 100 ampere argon arc. The conventional wisdom says that this is due to the higher ionization potential of helium (24.6 eV) as compared to argon (15.8 eV). It is assumed based upon the Saha equation that this will result in a higher arc temperature. Unfortunately, based on the arguments presented above and on experimental measurements [Key, 1983], there is not a higher temperature in the helium welding arc; and even if there were, it could not explain the much greater melting efficiency when using helium. The correct explanation lies in the variation of the thermal conductivity of the gases.

Although eighty percent of the heat in the argon arc is carried by the electron current, twenty percent is due to heat conduction across a gas boundary layer at the anode surface. [Quigley et al., 1973; Dinescu and Pfender, 1980] Heat flow across this boundary layer is controlled by the thermal conductivity of the gas. For monatomic gases such as helium and argon, the thermal conductivity is controlled by the mass diffusivity of the atoms, which, according to the kinetic theory of gases, is proportional to the inverse square root of the mass of

the atom [Dunn and Eagar, 1986]. Thus, with an atomic weight ten times as great as helium, argon has a thermal conductivity only 30 percent as large as helium. All other factors being equal, helium will conduct three times as much heat across the boundary layer as will argon. Table 1 illustrates this point. Although only 20 percent of the heat entering the anode from the argon arc is conducted across the boundary layer, 43% of the heat in a helium arc will be conducted across the boundary layer. (These figures are only "back of the envelope" calculations. Many other parameters change when switching from argon to helium gas. Other factors such as anode voltage drop, electric current distribution, arc temperature or radiation will change, but by insignificant amounts as compared to the thermal conductivity.)

As pointed out by Giedt et al. [1989], the actual melting efficiency of the arc welding process is relatively low (i.e. on the order of 20 percent or less). Thus an increase of 40% in the heat supplied could double the volume of metal melted. This is why helium shielded arcs melt more metal than argon shielded arcs.

Shielding Gas	Electric Current	Conduction across gas boundary layer	Percent by conduction
Argon	80%	20%	20%
Helium	80%	60%	43%

Table 1. Relative Heat Transfer from the Welding Plasma in Argon and Helium Shielding Gases (All heat values normalized to 100% for argon).

In addition to these pure gases, this hypothesis can explain why gas mixtures such as 75 Ar - 25 He or 50 Ar - 50 He will increase the rate of heat transfer over that of pure argon. Such mixtures have a thermal conductivity intermediate to the two pure gases. The ionization potential theory completely fails to explain why argon rich mixtures increase the rate of heat transfer. Since only 5 to 30% of the arc need be ionized, gas mixtures of less than 70 percent He contain no He ions. [Kim, 1986] If the He does not ionize, its ionization cannot be used to explain the more efficient heat transfer.

One may also ask why Argon-5% H<sub>2</sub> shielding gases also transfer heat more efficiently than pure argon. Using the simple mass diffusivity, thermal conductivity relationships presented above with a simple rule of mixtures, one would conclude that Ar-5% H<sub>2</sub> would have approximately a 25% greater thermal conductivity than pure argon. This cannot explain the greater rate of melting observed as this increase in thermal conductivity would result in only a 5% increase in the amount of heat transformed to the anode. The explanation in this case is due to a third mechanism of heat conduction. In addition to the flow of the electric current and the thermal conductivity across the gas boundary layer, diatomic gases such as hydrogen also have an enhanced thermal conductivity due to dissociation of the gas in the

plasma and recombination in the gas boundary layer. This enhancement of thermal conductivity in polyatomic gas plasmas is known as the reactive thermal conductivity. [Dunn, 1984] In fact, the thermal conductivity of Ar-5% H<sub>2</sub> is enhanced even more than 25% over that of pure argon, due to this contribution of the reactive thermal conductivity.

### 3. THE TEMPERATURE OF THE WELD POOL

Having shown that the temperature of the arc is an essentially irrelevant parameter in arc welding, one may then turn to the weld pool. The temperature of the weld pool is crucial as it will affect heat loss into the surrounding solid, the structure of the solidifying metal, the generation of vapors, welding fume, etc. It is commonly assumed that the temperature of the weld pool surface must be at the boiling temperature of the metal. At first glance, this may appear reasonable: there is vapor coming off the pool, forming welding fume. In addition, the surface of the pool is in contact with the plasma which is at a temperature well in excess of the boiling temperature of the metal. Again, unfortunately, such an obvious and simple assumption is incorrect. It is true that fume is escaping, but that does not prove that the metal is boiling. One sees large amounts of steam lifting from the surface of a hot pan of water that is clearly not boiling. Boiling represents the temperature at which the vapor pressure equals the ambient pressure. Large amounts of water can be vaporized in a one atmosphere kitchen from a pot of 80°C water.

In addition, the surface of the weld pool is not in direct contact with the hot plasma. It is separated by the much cooler gas boundary layer, the temperature of which is variable and generally unknown. How then can one estimate the temperature of the weld pool surface?

Cobine and Burger [1955] provided the clue to answering this question. When vapor escapes from a liquid, it carries away the heat of vaporization. Clearly, the mass of metal vapor lost from the weld pool times this heat of vaporization cannot exceed the rate at which the heat is being supplied to the surface by the arc (or the flame or electron beam or laser as the case may be). Thus the vaporization heat loss cannot be greater than the heat input or the weld pool will freeze!! Using this approach, Block-Bolten and Eagar [1982, 1984] showed that the maximum surface temperature for steel weld pools is approximately 500°C below the boiling temperature. This analysis has been enhanced by Cieslak et al. [1988] and has been shown to be correct experimentally by Krauss [1987].

### 4. DEPRESSION OF THE WELD POOL SURFACE

Anyone observing an actual arc weld will note that the surface of the metal is depressed beneath the arc. Since it is well known that a plasma jet exists in the arc [Maecker, 1955] and that this jet exerts a force on the weld pool [Lancaster, 1986, p. 223-224; Lin and Eagar, 1986] it is commonly assumed that the surface depression is due to the arc force. Again, unfortunately this is not true, at least not always. Lin and Eagar [1985] used their

measurements of the arc force [1986] to calculate the surface depression of a liquid metal pool. The results showed that the small (approximately one millimeter) depression observed at welding currents of less than 250 amperes can be explained by the plasma jet force, but above this current the measured force is nearly an order of magnitude too small to explain the observed surface depression. They provided a new explanation showing that convection within the weld pool may explain the deeper surface depressions observed at currents between 250 and 600 amperes. Above this current, the arc force may again become dominant since it increases as the square of the welding current.

### 5. ARC EFFICIENCY

The arc efficiency, commonly defined as the heat entering the metal divided by the total heat in the arc, is a key parameter influencing the rate of welding. Estimates of this parameter for different processes can vary from 20% to 99% [Lancaster, 1986, p. 164] but can vary over nearly as wide a range when comparing the same process [Giedt et al., 1989]. Since this efficiency is an important feature of nearly every heat flow model of the arc welding process, one would hope to know its value more precisely. Fortunately, Giedt [1989] has finally explained much of the confusion. He has shown that the definition of efficiency in a heat transfer model is more complex than the simple one used experimentally. Indeed, many of the more careful experimental tests agree that the efficiency of heat transfer to a gas tungsten arc anode is approximately 80%; however, the value of efficiency which is used in a mathematical model of heat transfer in the weld, is dependent on the details of the model. This is not a very obvious conclusion, even after it is pointed out so well by its author. Nonetheless, some careful thought concerning its cause and implications suggests that it is a correct conclusion. Essentially one should consider that small variations in the temperature gradients near the heat source, will create large variations in the integrated heat flux into the entire sample. Since the arc efficiency represents this heat flux integrated throughout the sample, a small error in estimation of the temperature gradient near the arc source can result in a large change in the integrated heat flux throughout the sample, even though the calculated temperature distribution appears to be (and is!) very similar to the actual temperature distribution. An attempt to illustrate this is given in Figure 1. Although the shape of the two calculated temperature profiles is similar and they are very close in space, the efficiency used to provide model agreement with experiment must be greater for the distributed heat source model and must be less for the point heat source model.

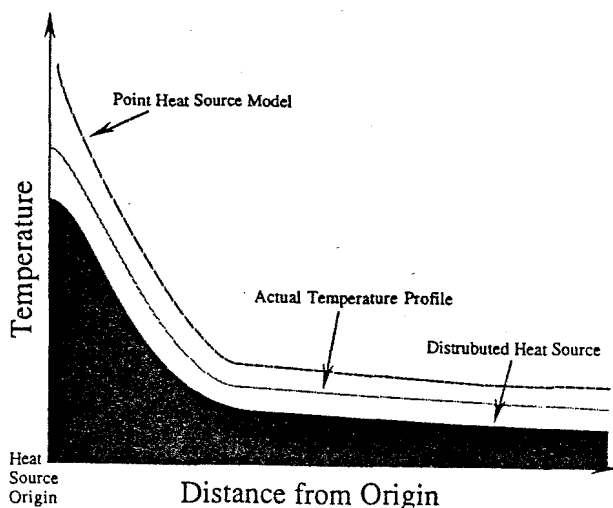


Figure 1: Schematic showing how small variations in initial conditions near the heat source origin can create similar overall curve shapes, but larger variations in integrated heat efficiencies.

### 6. DROPLET FORMATION IN CONSUMABLE ELECTRODE WELDING

There are several theories which attempt to describe the size of drops which melt off the end of a consumable electrode. In Lancaster's book some 20 pages (p. 56-76) are devoted to the pinch instability theory, whereas only one page is devoted to the static force balance theory which is by far the more correct theory (Section 3.7.1 on pp. 54-55 of Lancaster).

The pinch instability theory is a variation of the Rayleigh instability in which a long cylindrical column of liquid is found to break up into spherical drops. In the pinch instability theory, the electromagnetic pinch force in a current conducting liquid cylinder perturbs the cylinder such that it breaks up into spherical drops. It is shown that the pressure in the radial direction varies with increasing current, producing drops that become smaller as the current increases. Since smaller drops with increasing current is an experimentally observed fact in consumable electrode welding, it is assumed that the pinch instability theory works. Again, this is an incorrect hypothesis.

Firstly, in the vast majority of electrode melting conditions, no liquid cylinder exists. There is only a small drop of liquid metal on the end of a solid electrode. It is somewhat trivial to consider drops breaking down into drops. The only time that a liquid cylindrical column exists is in the advanced stages of streaming transfer, which from a practical viewpoint is of little use. Nonetheless, the pinch instability theory may be applicable in this very restricted range of operating conditions. In all other conditions, when no liquid cylinder exists, the pinch instability theory is incorrect.

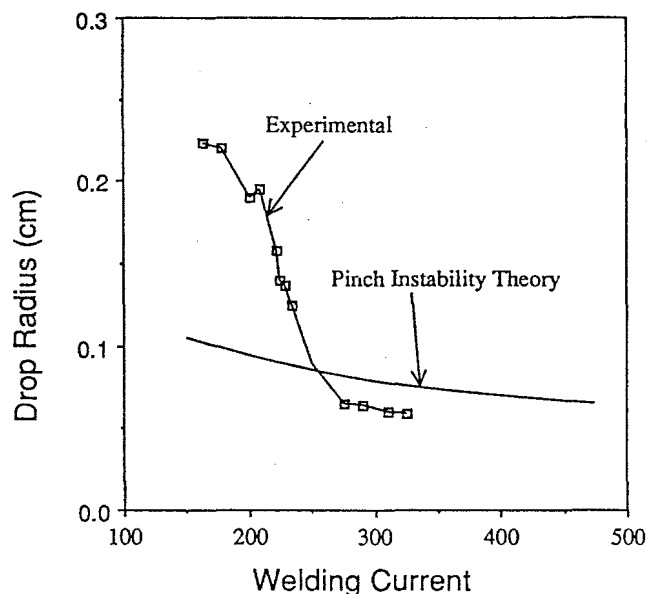


Figure 2: Comparison of experimentally measured GMAW droplet size as a function of welding current with the droplet size predicted by the pinch instability theory. 1.6 mm diameter steel electrodes with 2.6 cm electrode extension beyond the contact tip. The shielding gas is argon - 2% oxygen. [Kim, 1989]

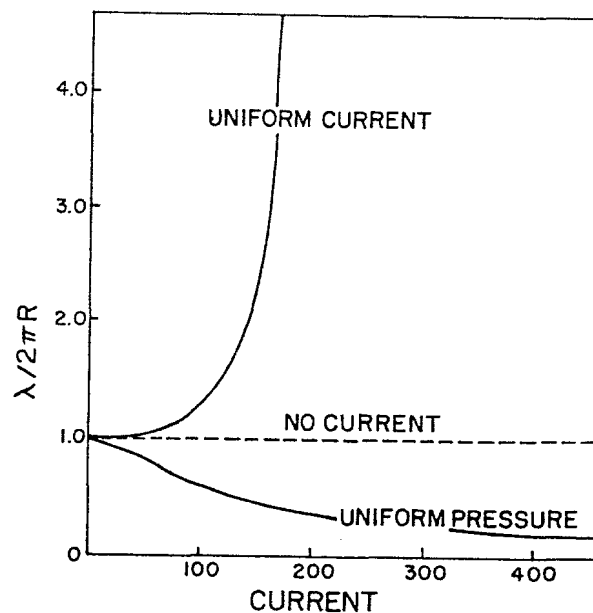


Figure 3: Calculation of the critical wavelength of instability for a liquid cylinder breaking up into drops under the conditions of a) uniform electromagnetic radial pressure in the cylinder and b) uniform radial current distribution. Condition b) is more realistic of the welding process. [Kim, 1989]

Secondly, when one puts values into the pinch instability equation for droplet size, one obtains the results shown in Figure 2 [Kim, 1989]. Clearly both the shape and the magnitude of the curve are incorrect. Finally, when one includes the stabilizing effect of a uniform current distribution in the electrode on the pinch instability solution, which produces a radial pressure gradient in the liquid cylinder, one finds that drops will not form. (See Figure 3) Traditional pinch instability solutions for welding have assumed that the pressure along the central axis of the cylinder was equivalent to a radially uniform pressure. [Lancaster, 1986] While Figures 2 and 3 show that this uniform pressure assumption gives the correct trend of decreasing drop size with increasing current, the more realistic condition of a uniform current distribution shows that the pinch instability cannot be used to explain droplet formation in GMAW.

## CONCLUSION

This paper has presented a number of examples where seemingly obvious explanations could not withstand a more thoughtful or a more quantitative explanation. The lesson to be learned is twofold. Firstly, one should not accept an explanation merely because it appears obvious (or because it appears in print!). It is necessary to ask further questions of oneself about the details of the model or of the implications of the model on other portions of the system. If inconsistencies are found, further investigation is warranted.

Secondly, after an hypothesis has withstood the questioning mentioned above, it is necessary, if possible, to become quantitative. Many otherwise viable theories (like the plasma jet causation of surface depression) are found to fail this second test. Indeed, Lord Kelvin put it this way:

I often say...that when you can measure what you are speaking about, and express it in numbers, you know something about it; but when you cannot measure it, when you cannot express it in numbers, your knowledge is of a meagre and unsatisfactory kind; it may be the beginning of knowledge, but you have scarcely, in your thoughts, advanced to the stage of science, whatever the matter may be.

If the field of welding is to progress at the rate of allied sciences, it is necessary to become more self-critical of our knowledge and to be bold in quantifying what we know. It is not sufficient to work tirelessly in the laboratory and in the factory. We must work intellectually, both to advance the field and to gain the respect of those who work in more scientific fields.

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