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The Physics of Welding Processes

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Abstract

Welding is an extremely complex process; however, due to its commercial importance, it is essential that a more thorough study of the various processes be undertaken. Three examples of recent advances in welding physics are presented. The first example uses an analysis of anode spot behavior and heat flow to select the best shielding gases for pulsed current GMAW. The second example illustrates how differences in heat transfer coefficient between the sheet and the copper electrode in resistance spot welding can influence the ability to control the process. The third example shows how modification of a braze alloy composition can result in a Transient Liquid Phase diffusion bond possessing much greater ductility and reliability.

1. Introduction

An extremely wide variety of welding processes is used commonly in commercial fabrication. The average engineer or scientist rarely considers the extent to which we regularly trust our safety and our lives on the quality and reliability of welded connections. These connections occur so frequently and are made so routinely that we lose sight of the extreme complexity of the welding process. Yet whenever one of these joints fails in a dramatic manner, society asks why the process was not developed or performed more carefully.

The complexity of welding is readily apparent when one considers that fusion welding involves temperature gradients of thousands of degrees, over distances of less than a centimeter, occuring on a time scale of seconds, involving multiple phases of solids, liquids, gases and plasma. Indeed, this complexity causes most scientists to shun welding as unscientific and unworthy of thoughtful analysis. It is only the true engineer who is willing to deal with a process of such exceeding complexity in order to achieve the end result of a fabricated product of commercial and societal usefulness. One of the challenges facing those who engineer welded structures and components, is communication of the importance and significance of welding to other scientists and to the general public. One of the purposes of this paper is to describe some of the complexity of several welding processes, and to demonstrate how an understanding of the process physics can help to improve the quality and reliability of the product. Three examples have been chosen, in part because of my familiarity with these processes and in part due to the relationship of these processes to other research presented during this conference.

The first example concerns the formation of metal droplets on the end of gas metal arc welding (GMAW) electrodes, and the influence of shielding gas composition on the process. The second describes new measurements of heat flow in resistance spot welding of thin gauge galvanized steels, commonly

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used in automobile production, while the third shows how a simple modification of brazing alloy composition can produce a much more reliable dissimilar metal joint.

2. Droplet Formation in GMAW

Photography of the gas metal arc process shows that the anode spot corona varies markedly with different shielding gases. With helium or carbon dioxide shielding, the anode spot is attached to the bottom of the pendant drop on the end of the electrode. The size of the spot does not change markedly as the current increases. With argon, the anode spot is more diffuse and grows noticably in size as the current increases. At sufficiently high currents (for example, above 230 amperes with 1.6 mm diameter steel electrodes) the anode spot fills the molten drop and begins to climb the cylindrical side walls of the electrode. Since most of the heat carried to the anode is carried by the welding current, the current in the anode spot causes the cylindrical side walls of the electrode to melt [Y.S. Kim, 1989]. The end of the electrode forms a tapered geometry as shown in Figure 1. Such a tapered electrode tip geometry does not develop in pure helium or pure carbon dioxide shielding gases.

The tapered tip creates a smaller diameter for attachment of the droplet to the electrode by surface tension forces [Y.S. Kim, 1989]. This produces smaller droplets than would be present in the absence of taper formation. The smaller droplets formed with argon shielding from a tapered electrode are seen clearly in Figure 2, as compared with helium and carbon dioxide shielding.

The formation of the taper occurs during gas metal arc welding of steel, aluminum and titanium, when using argon shielding gas [Y.S. Kim, 1989]. There are a number of consequences of this taper formation. Firstly, Y.S. Kim [1989] has shown that the melting rate of the electrode is controlled by heat transfer across the liquid-solid boundary between the drop and the solid electrode. Since the taper reduces the area of this boundary, taper formation reduces the rate of melting of the electrode. At high currents, the melting rate in helium and carbon dioxide is greater than in argon due to absence of the taper. Thus the greater melting rate in helium is not due to the higher ionization potential of this gas as is commonly assumed [Eagar, 1990], but to a larger liquid-solid contact area in which heat is transferred to the solid electrode.

Secondly, Y.S. Kim has shown that the formation of a taper can reduce the range of one drop per pulse transfer in pulsed current GMAW. As the drops become smaller with argon shielding gas due to taper formation, the pulsing frequency must increase accordingly. By suppressing the formation of the taper, both large and small drops can be released from the end of the electrode during pulsed current welding. The largest drops are equal to the droplet size created at the low current portion of the pulse in the absence of the taper, while the smallest drops are equivalent to those produced during the peak of the current pulse. This greatly increases the range of frequencies which are permissible for one drop per pulse operation [Y.S. Kim and Eagar]. By addition of helium or carbon dioxide to the argon shielding gas, the anode spot is constricted and does not climb the cylindrical side walls of the electrode as readily. Thus taper formation is suppressed and the acceptable range of frequencies for pulsed current GMAW is broadened and the process becomes more easily controlled. This example illustrates how an understanding of the physics of droplet formation can aid the welding engineer in selection of the best shielding gas composition for pulsed current gas metal arc welding.

3. Resistance Spot Welding of Galvanized Steel Sheets

In recent years, there has been increased use of thin gauge (less than one millimeter) galvanized steel in automotive applications. Current plans call for 0.6 mm sheet in some new models.

Using a simple parametric analysis, it is found that approximately 30 percent of the heat generated in resistance spot welding of 1.2 mm thick galvanized sheet is used to heat and melt the weld metal, 15 percent is lost to the surrounding heat affected zone and 55 percent is lost by conduction into the copper electrodes [E.W. Kim and Eagar, 1988]. When one welds 0.6 mm thick galvanized steel, these proportions would change to approximately 15 percent to melt the weld metal, 7 percent in the HAZ and 78 percent lost to the electrodes.

In more recent work, E.W. Kim [1989] has used an infrared camera technique [E.W. Kim and Eagar, 1989] to measure the heat transfer coefficient between the copper electrode and the steel sheet during the spot welding process. Some of his results are presented in Table 1. It is readily seen that a steel sheet with a heavy zinc coating may lose three times as much heat to the copper electrode as will an uncoated steel. This is the reason why galvanized steels require higher welding currents than do bare steels.

It will be noted that the variation from spot to spot on a single type of steel may vary by 10 to 20 percent, whereas changes in the local coating thickness from 35 g/mm^2 to 100 g/mm^2 will cause a 250 percent variation in the heat lost to the electrodes. From this information one can readily see why thin gauge galvanized steel is so much more difficult to weld than is bare steel of the same thickness. If 15 percent of the total heat is needed to melt the weld metal and 78 percent plus or minus an 8 percent variation is lost to the electrodes, identical material welded under identical conditions can produce either expulsion or no weld from spot to spot based solely on local variations in the heat transfer coefficient. When one mixes steels of different coating thickness, it is impossible to produce a machine setting which can weld all coatings equally. This analysis shows that the resistance welding process for thin gauge galvanized steel is inherently uncontrollable. A solution to this problem would be modification of the steel or the electrode surface in order to reduce the heat transfer coefficient to an acceptably small value.

4. Brazing of Copper to Molybdenum

There are two main applications for copper to molybdenum joints. Firstly, in microwave amplifier circuits for radar applications, copper is used to conduct heat away from the core of the component whereas the hot face consists of a Mo insert brazed to a copper fin. Secondly both copper and molybdenum are incorporated into ceramic/metal joints to reduce the residual stresses that accrue from a mismatch in the coefficient of thermal expansion between the ceramic and the metal. Copper plastically deforms during the post joining cooldown whereas Mo possesses a low coefficient of thermal expansion. These applications demand that Cu/Mo joints possess high strength and ductility.

Au-18%Ni alloy and Au(35%)-Cu(62%)-Ni(3%) alloy were investigated as potential brazing interlayers for these joints. Subsequent mechanical tests indicated that the Au-Cu-Ni interlayer led to joints that possessed a very large degree of ductility whereas joints fabricated using the Au-Ni alloy were very brittle and exhibited little if any ductility.

Metallographic examination of the brazed joint (using a scanning electron microscope, SEM, equipped with an energy disersive X-Ray analyzer, EDX) revealed the presence of Ni-Mo intermetallics at the interface of the Au-Ni alloy and the molybdenum base metal (Fig. 3). In contrast, it was difficult to discern the plane of joining for samples brazed with the Au-Cu-Ni brazing alloy (Fig. 4) even at high magnification (> 1000X). Further, the interface was wide in the case of the Au-Ni alloy whereas it was much thinner in the case of the Au-Cu-Ni alloy.

These differences may be explained by consideration of the binary phase diagrams coupled with quantitative EDX analysis at several locations. The crucial phase diagram is the Au-Cu diagram. The Au-18%Ni alloy was brazed at 975°C. From the Cu-Au diagram it is clear that the Au in the alloy must have dissolved a large portion of the Cu base metal (Au will continue to erode the Cu base metal till the overall composition of the liquid is approximately Cu-30%Au. This corresponds to the solvus-liquidus equilibrium at 975°C in the Au-Cu system on the Cu rich side). The large fraction of Ni in the alloy led to the formation of Ni-Mo intermetallics at the Mo-braze alloy interface.

In contrast, the Au-Ni-Cu alloy possesses a Au:Cu ratio of 35:62. From the Au-Cu diagram, this implies that the Au-Cu-Ni alloy will dissolve very little of the Cu base metal before isothermal solidification commences. This explains the observed difference in the width of the interface. EDX analysis of the interface confirmed that the Au from the interlayer had diffused into the Cu. The gradient in Au concentration clearly indicates that isothermal solidification occurred during joining.

The joint fabricated using the Au-Ni alloy exhibited a distinct interfacial region across which little diffusion and homogenization had occurred. This and the presence of intermetallics led to a poor joint in the case of the Au-Ni alloy. Hence, the Au-Cu-Ni alloy which solidified isothermally was chosen as the brazing alloy.

Thus this example has shown that a fundamental understanding of the phenomena occuring at the joint can significantly improve the quality of the final brazed joint.

5. Conclusion

It is seen that an understanding of the process physics can make a very complex process such as welding or brazing, appear much clearer. By understanding the process, it becomes easier to control and easier to modify to ensure that high quality, reliable joints are produced. With so many joining processes and with an ever increasing number of materials to be joined, there is ample opportunity for many people to contribute to a better understanding of the physics of welding processes.

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Material	Heat Transfer Coefficient	Standard Deviation
Bare Steel	0.055	0.013
Zn coated, 35 g/mm^2	0.066	0.015
Zn coated, 68 g/mm^2	0.082	0.013
Zn coated, 100 g/mm^2	0.162	0.015
A40	0.058	0.010
E70	0.080	0.013
G60	0.089	0.010

Table 1. Measured Contact Heat Transfer Coefficient Between Copper Resistance Welding Electrode and Steel Sheet in $W/mm^2 \cdot {}^oC$.