

KEYNOTE ADDRESS
THE PHYSICS AND CHEMISTRY OF
WELDING PROCESSES

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Abstract

Historically, welding processes have developed empirically and have been applied to technological problems with unusual quickness. As a result, a large number of processes have evolved, many of which are not well characterized from a scientific point of view. Many attempts have been made to categorize these processes, mostly with disappointing results; however, there have been a few categorizations which have proven useful. The first considers the thermodynamic stability of surface contaminants and describes how the temperature, pressure and chemical potential of the welding system can be changed to eliminate these contaminants. The second describes the heat intensity on the surface of the material and relates this to the maximum weld travel speed, the heat affected zone width, the equipment cost and the minimum sampling frequency necessary to control the process.

THE NEED FOR WELDING AND JOINING is ubiquitous; there are very few manufactured products that do not rely on welding or joining in some form. Indeed, only monolithic parts can be made without joining. Unfortunately, our methods are generally imperfect, either in properties or in affordability; and there is a constant search for improved processes.

The perfect joint is one which is indistinguishable from the material surrounding it. Some processes, such as diffusion bonding, come very close to this ideal; however, such processes seem to be either cost intensive or restricted to a narrow group of materials. It is clear that there is no universal process which will perform adequately on all materials and in all geometries. As a result, a welding engineer must be able to wisely select the best process for a particular material in a given application. In order to do this, it is useful to categorize the various welding processes in a

systematic, scientifically based manner. If this can be achieved, it may be possible to determine the strengths and weaknesses of a given process a priori.

Given the great economic importance of welding to any manufactured product, one might ask why a fundamental science has not developed around this field? There are several answers to this question. Firstly, welding itself is not a discipline but is a process. As with any process, it involves scientific principles from many different disciplines, e.g. physics, chemistry, mechanics, electronics, materials and the like. In this sense, there is a science base for welding already in existence. It is up to the welding engineer to search out the knowledge available in other fields and to apply it, judiciously, to the problems of welding. The study of welding cannot be expected to create new science. Rather, it is an eminently practical field of study which can bring the promises of science to each of us in our daily lives. It is this practical application of science which makes the study of welding so exciting for many of us.

Ironically, this great need for improved welding processes is the second reason why a fundamental science has not been built around welding. Virtually any new process which might be applicable to welding is tested on welding immediately after it is discovered. Some of the earliest experiments on electric arcs during the nineteenth century involved welding. Electron beams and lasers were used to weld small wires together within a few years after these new heat sources were discovered. It is even rumored that particle beams have been used to make welds. Some of these new heat sources were adapted for practical use in welding long before we understood the fundamentals of how the heat source interacts with the material. In many cases, our use of a given process has far exceeded our science base. As a result we often experience unexpected problems. Progress is being made, but it is slow. The papers in this

conference illustrate the areas of greatest concern in welding and joining today.

WELDING PROCESS FUNDAMENTALS

It would behoove us to develop a scientific framework which will allow us to evaluate existing and potential new welding processes. To do this, we must look back at what we are trying to achieve. As noted previously, we wish to form a joint which has indistinguishable properties from the material surrounding it. Ideally, one would like to merely place two parts in contact and achieve a perfect bond. There are two fundamental problems which prevent this. First, the surfaces of any material in the atmosphere is contaminated with either oxygen or water vapor or carbon dioxide. Second, the parts to be joined are solid and the surfaces to be joined do not mate perfectly. Diffusion bonding overcomes these chemical and geometric incompatibilities by application of heat and pressure. The heat allows the surface contamination to diffuse into the bulk. Further, the heat permits sufficient deformation or shape change to promote perfect mating of the surfaces. In materials such as iron, titanium or copper, which dissolve all or most of their usual surface contaminants, a nearly perfect bond can be made; but in aluminum or other metals with refractory oxides which are insoluble in the base metal, the process does not work so well.

Indeed, diffusion or other forms of solid state bonding achieve remarkable results. Even materials which are immiscible in both the solid and liquid states, such as iron and silver, can form interfacial bonds of exceptional strength. O'Brien, Rice and Olson achieved tensile strengths of nearly 100 ksi when bonding maraging steel with silver. (1) One of the reasons for this seemingly exceptional bond strength is that dislocations do not propagate across the bond interface; hence, near theoretical bond strengths are obtainable in principal. The theoretical iron-iron bond strength in the absence of dislocations is in excess of 1000 ksi; hence, even iron and silver which may not have a very high intrinsic bond strength can produce excellent interfacial tensile strength provided the interface is not contaminated or otherwise flawed.

Clearly then, we can achieve excellent results if we can eliminate the surface contamination. Since these are chemical bonds, we can look to chemical thermodynamics to determine how to eliminate them. The free energy of any bond is related to the temperature, pressure and chemical potential of the system, i.e.

$$G = G(T, P, \mu_i)$$

hence, to break a bond we must manipulate these fundamental variables. In fact this is clearly what we do in current practice, even if it is

not a conscious decision. For some materials, notably silver, with a low chemical affinity for oxygen, a few hundred degrees centigrade will cause the surface oxide to decompose. Silver will also dissolve the oxygen, which is one reason why O'Brien *et. al.* found such good diffusion bonding at low temperatures. (1) Nonetheless, the temperature must be maintained (and other contaminants such as sulfur must be kept out of the system) if one is to avoid reformation of the surface film. The monolayer time-pressure is on the order of 10^{-3} atm-seconds, so it is not practical to clean the surface at high temperatures and later cool it unless one is operating at extremely high vacuums.

In materials other than silver with somewhat more stable oxides, such as copper or iron, higher temperatures are necessary to decompose the oxide. One can estimate the temperature necessary for decomposition of the oxide by reference to Ellingham diagrams (see Figure 1); however, one must be cautious and remember that such diagrams are based on all solids and liquids being in their standard states (which is usually the pure form) and all gases, such as oxygen being at one atmosphere pressure. If the material is alloyed, the relative activity of each metal component must be known in order to calculate a decomposition temperature. Since the atmospheric oxygen pressure is not very different from one atmosphere (at least in the logarithmic sense of thermodynamics), correction for the oxygen activity difference is not very important if one is operating in the atmosphere. However, if the system is operated in an inert gas or a vacuum, the oxygen potential may vary markedly. In such cases, we are using the second variable in the free energy function to assist in decomposition of the surface oxide. Reducing the partial pressure of oxygen and elevating the temperature can reduce oxides of intermediate stability. These effects of temperature and pressure on reduction of the oxide of any metal is readily calculated by chemical thermodynamics.

For more stable oxides, the partial pressure can be further reduced by addition of a reactive gas. The AWS Brazing Manual provides a useful graph, reproduced in Figure 2, of the relative stability of a number of metal oxides as a function of temperature and oxygen pressure, in the presence or absence of a reducing gas such as hydrogen. Clearly, any welding process engineer should understand the chemistry behind such a graph when considering diffusion bonding or brazing as a joining process for a given material.

The third variable in the free energy equation is the chemical potential of a species. The common method of altering this variable involves both temperature and the use of a flux. The flux provides a system of very low chemical potential for the surface contaminant; hence, the surface film will be absorbed into the flux. This is perhaps the most common method of

removing surface contamination, yet, the specific chemistry of most flux systems is poorly understood.

In his classification of welding processes, Houldcroft describes this requirement of elimination of surface contamination as the "shielding method." He lists vacuum, inert gas, reactive gas, flux, no shielding and mechanical exclusion as possible methods. (3) It should be recognized that each of these shielding methods (with perhaps the exception of the last one) can be quantified in terms of the free energy of the system, as defined by the temperature, pressure and chemical potential of the surface contaminant. In this way, one can determine whether a shielding method is appropriate for a given material.

It will be noted that temperature is a major variable in nearly all methods of removing surface contaminants. This suggests another fundamental ranking for joining processes, i.e. the method of heating. In his classification Houldcroft called this the "source of heat", yet again, this can be quantified to yield more information about a given joining process. As before, one should choose an intensive, rather than an extensive variable to describe the system. A number of different authors have suggested that the relevant quantity is the power density on the surface of the material.

One of the primary welding processes is fusion welding since this solves both the chemical and the geometric problems of joining two surfaces. Melting the base material permits the surface contamination to float or dissolve away while the liquid metal conforms perfectly to the solid mating surface. Hence, heat used for welding usually involves melting the surface.

If one considers a planar heat source diffusing into a very thick slab, the surface temperature will be a function of both the surface power density and the time. Figure 3 shows how this temperature will vary on steel with power densities from 400 watts/cm² to 8000 watts/cm². (4) At 400 watts/cm², it takes two minutes to melt the surface. If the 400 watts/cm² heat source were a point on the flat surface, the heat flow would be divergent and it might not even be possible to melt the steel; the solid metal might be able to conduct away the heat as fast as it is being introduced. Generally, it is found that heat source power densities of approximately 10³ watts/cm² are necessary to melt most metals.

At the other end of the power density spectrum, it is found that heat intensities of 10⁶ or 10⁷ watts/cm² will cause vaporization of most metals within a few microseconds. Above these power densities, all of the solid interacting with the heat source is vaporized and no fusion welding can occur. Thus it is seen that the heat sources for all fusion welding processes lie between approximately 10³ and 10⁶ watts/cm² on the power density spectrum.

The spectrum with the locations of several common joining processes is shown in Figure 4.

Inspection of Figure 1 shows that the power density is inversely related to the interaction time of the heat source on the material. Since this is a transient heat conduction problem, one can expect the heat to diffuse into the steel to a depth which increases as the square root of time, i.e. from the Einstein equation

$$x = \sqrt{at}$$

where: x is the distance that the heat diffuses into the solid, in cm
a is the thermal diffusivity of the solid, in cm²/sec, and
t is the time in seconds

For the planar heat source on a steel surface as represented by Figure 3, one finds the time in seconds to produce melting on the surface, t_m, is given by:

$$t_m = \left[\frac{5000}{H.I.} \right]^2$$

where H.I. is the heat intensity in watts/cm². If we consider the time to melting to be equal to the necessary interaction time, t_I, of the heat source with the material, one can generate the graph shown in Figure 5. One can see that heat sources of the order of 10³ W/cm², such as oxyacetylene flames or electroslag welding require interaction times of 25 seconds in steel while laser and electron beams at 10⁶ W/cm² need interaction times on the order of 25 microseconds. If we divide this interaction time into the heat source diameter, d_H, we obtain a maximum travel speed, V_{max} for the welding process, as shown in Figure 6. From this, it is clear why welders begin their training with the oxyacetylene process as it is inherently slow and does not require rapid response time in order to control the size of the weld puddle. Greater skill is needed to control the more rapid fluctuations in arc processes, while no human can control the pool of the high heat intensity processes such as laser and electron beam. It is an inherent fact that these processes must be automated in order to control them. This need to automate leads to increased capital costs for these high heat intensity processes. One can approximately replace the number of watts/cm² of a process with the dollar cost of the capital equipment.

For constant total power, a decrease in the spot size will produce a squared increase in the heat intensity. This is one of the reasons why the spot size decreases with increasing heat intensity as shown in Figure 6. It is easier to make the spot smaller than to increase the power rating of the equipment. In addition, one generally wishes only to melt a small volume of material. If the spot size were kept constant and the input power were squared in order to

obtain higher power densities, the volume of fused metal would increase dramatically, with no beneficial effect. However, this decreasing spot size, coupled with a decreased interaction time at higher power densities, compounds the problem of controlling the higher heat intensity process. A shorter interaction time means that the sensors and controllers for automation must operate at higher frequencies. The smaller spot size means that the positioning of the heat source must be even more precise. This positioning accuracy must be on the order of the heat source diameter, d_H , while the control frequency must be greater than the travel velocity divided by the diameter of the heat source. For processes operating near the maximum travel velocity, this is the inverse of the process interaction time, t_I (see Figure 5).

Thus we see that not only must the high heat intensity processes be automated due to an inherently high travel speed, but the fixturing requirements become greater and the control systems and sensors must have ever higher frequency response. Both of these factors lead to increased costs of high heat intensity processes, which is one reason that these processes, which are very productive, have not found wider utilization.

Another important welding process parameter that is related to the power density of the heat source is the width of the heat affected zone. Using the Einstein equation one can estimate a heat affected zone width from the process interaction time and the thermal diffusivity of the material. This is shown in Figure 7 with one slight modification. Above about 10^4 W/cm² the heat affected zone width becomes roughly constant. This is due to the fact that the HAZ grows during the heating stage at power densities below 10^4 W/cm² but it grows during the cooling cycle at higher power densities. Thus at low power densities, the HAZ width is controlled by the interaction time, while at high power densities it is independent of the heat source interaction time. In this latter case, the HAZ width is controlled by the cooling time necessary to remove the heat of fusion from the weld metal. In such a case the HAZ width is proportional to the fusion zone width.

The change of slope in Figure 7 also represents the heat intensity at which the heat utilization efficiency of the process changes. At high heat intensities, nearly all of the heat is used to melt the material and little is wasted in preheating the surroundings. As the heat intensity decreases, this efficiency is reduced. For arc welding, it may be only one-half of the heat entering the plate and for oxyacetylene it may be 10 percent or less.

Finally, the heat intensity also controls the depth to width ratio of the molten pool. This can vary from 0.1 in low heat intensity processes to more than 10 in high heat intensity processes.

CONCLUSION

It is seen that there are fundamental chemical and physical limits to our selection of welding processes. The chemical stability of surface contamination influences our choice of shielding or surface removal during the process. A knowledge of the power density on the surface of the material produces quantifiable parameters which provide criteria for maximum travel speed, minimum frequency of process control systems, heat affected zone width and equipment cost. Although these criteria are only approximations and will not define any process precisely, they do provide guidelines from which to predict how a new process or a new material will behave. Intelligent application of such guidelines can often help in the selection or application of a wide range of welding processes on a variety of materials.

Acknowledgements

The author wishes to express his sincere appreciation to Dr. Bruce MacDonald of the Office of Naval Research and Dr. Robert Reynik of the National Science Foundation for a decade of support on the physics and chemistry of welding processes. This generalized approach to welding process could only have been developed through such a long term commitment to the study of a number of different welding processes.

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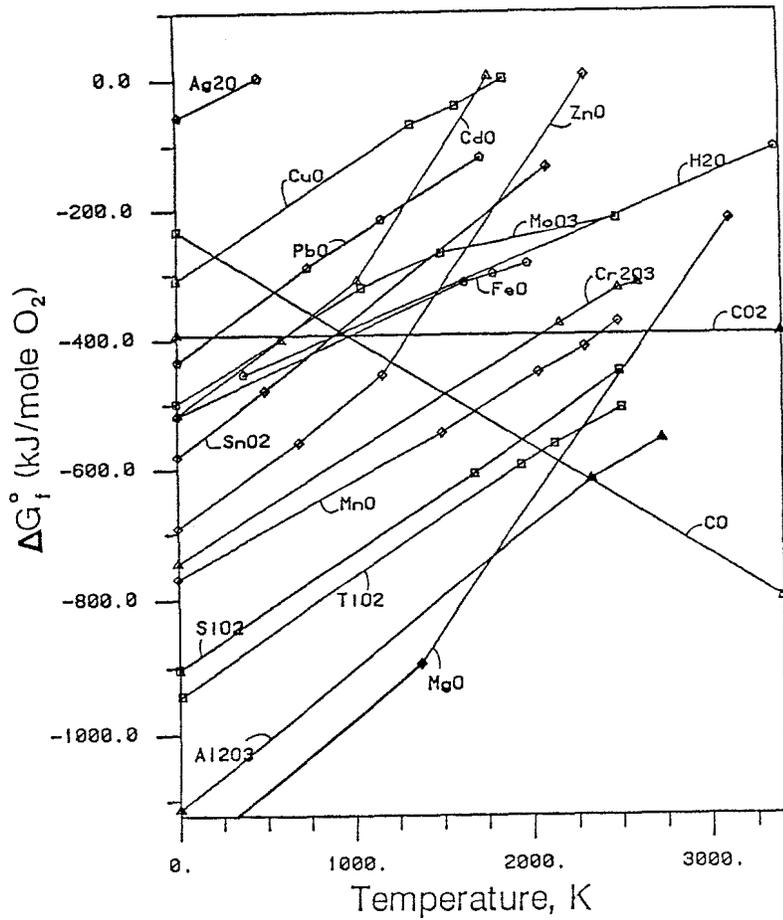


Figure 1
Ellingham diagram illustrating the relative thermodynamic stability of a number of metal oxides.

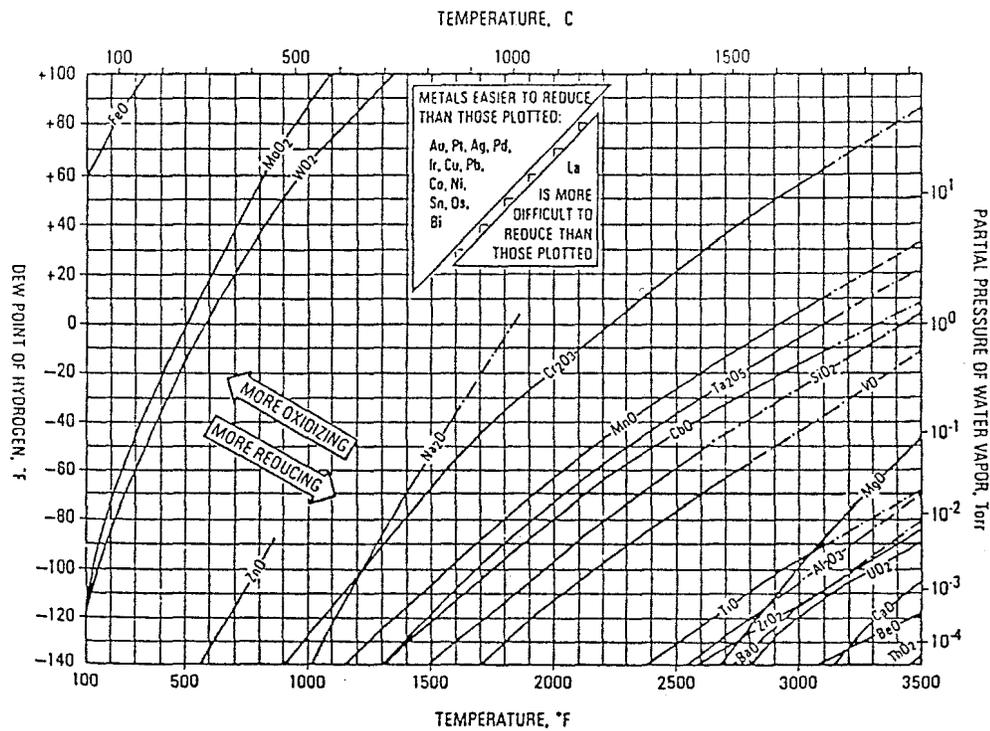


Figure 2
Metal-metal oxide equilibria in hydrogen atmospheres. From the AWS Brazing Manual, used by permission.

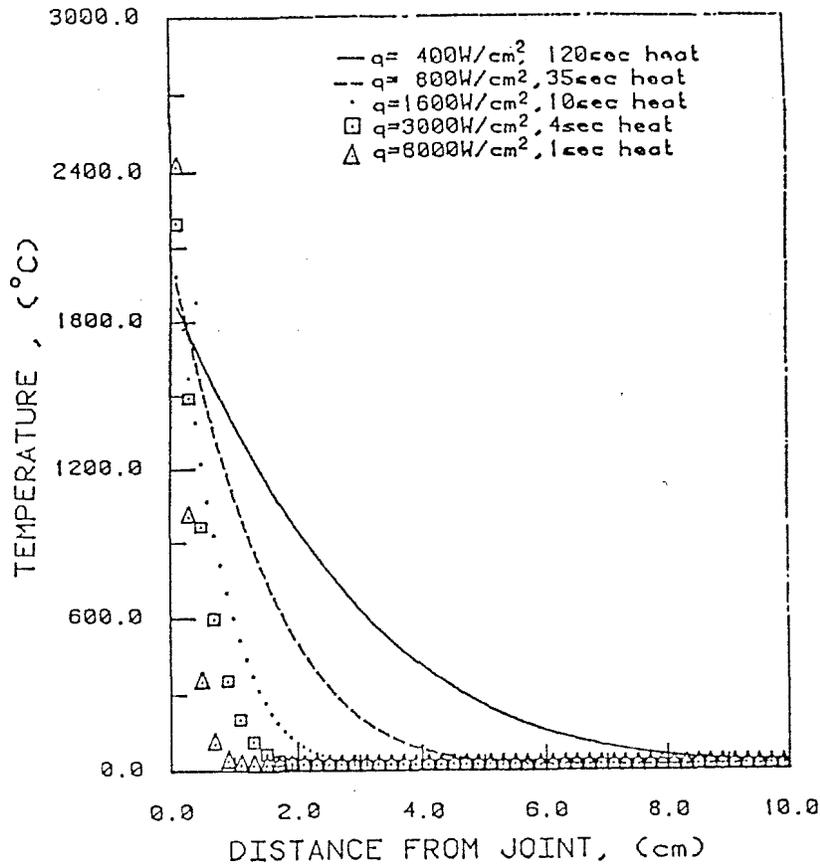
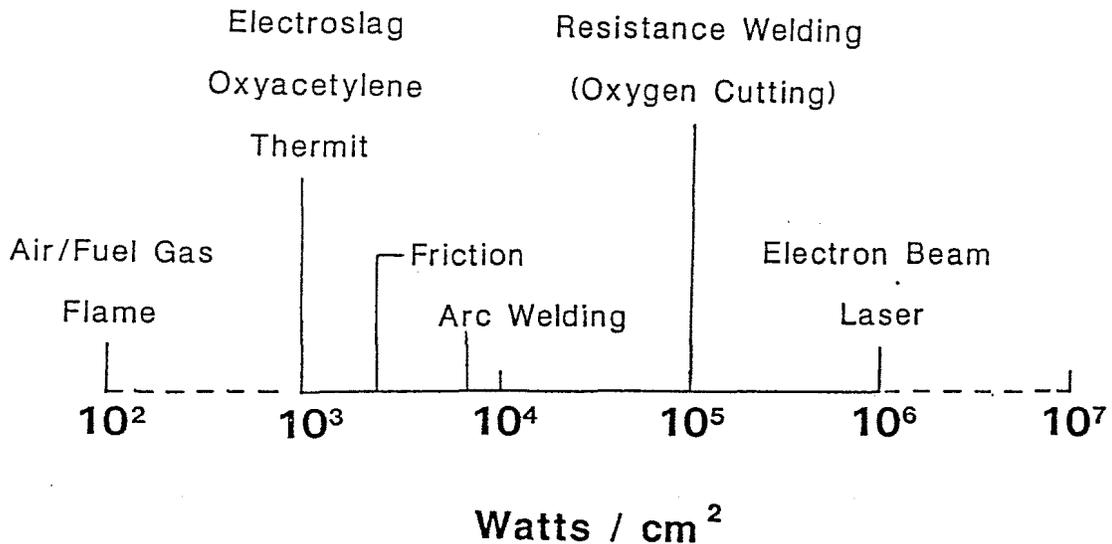


Figure 3

Temperature distribution after a specific heating time in a thick steel plate, heated uniformly on one surface as a function of applied heat intensity. The initial temperature of the plate is 25°C.

Figure 4

Spectrum of practical heat intensities used for fusion welding.



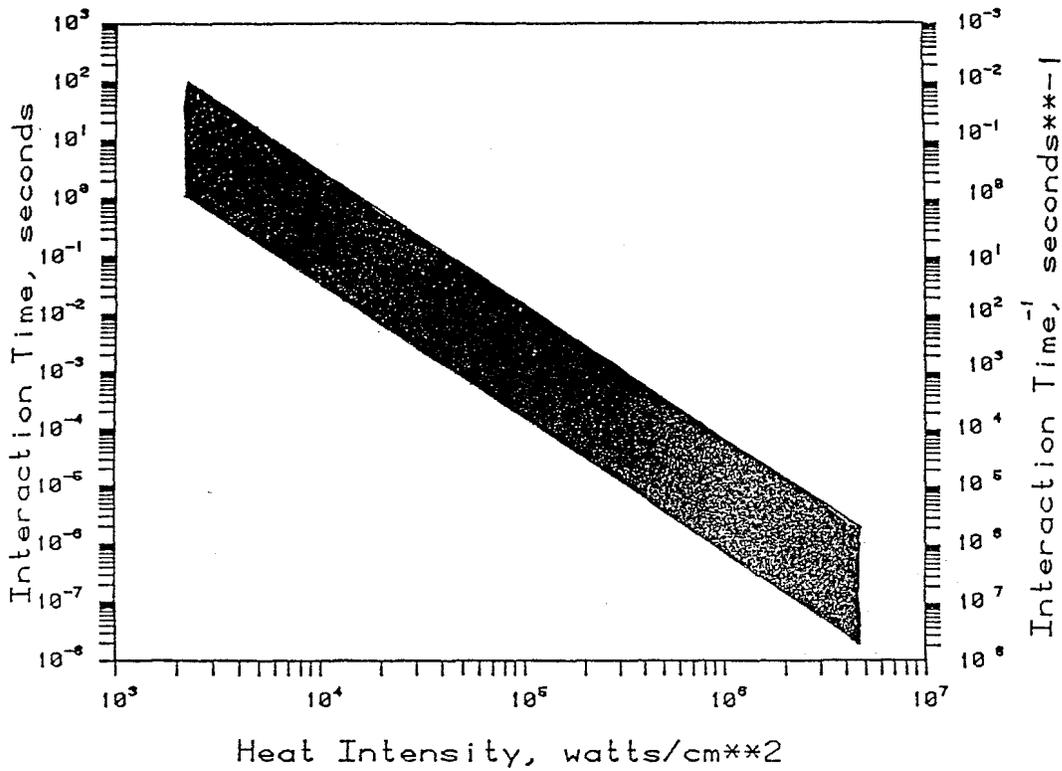
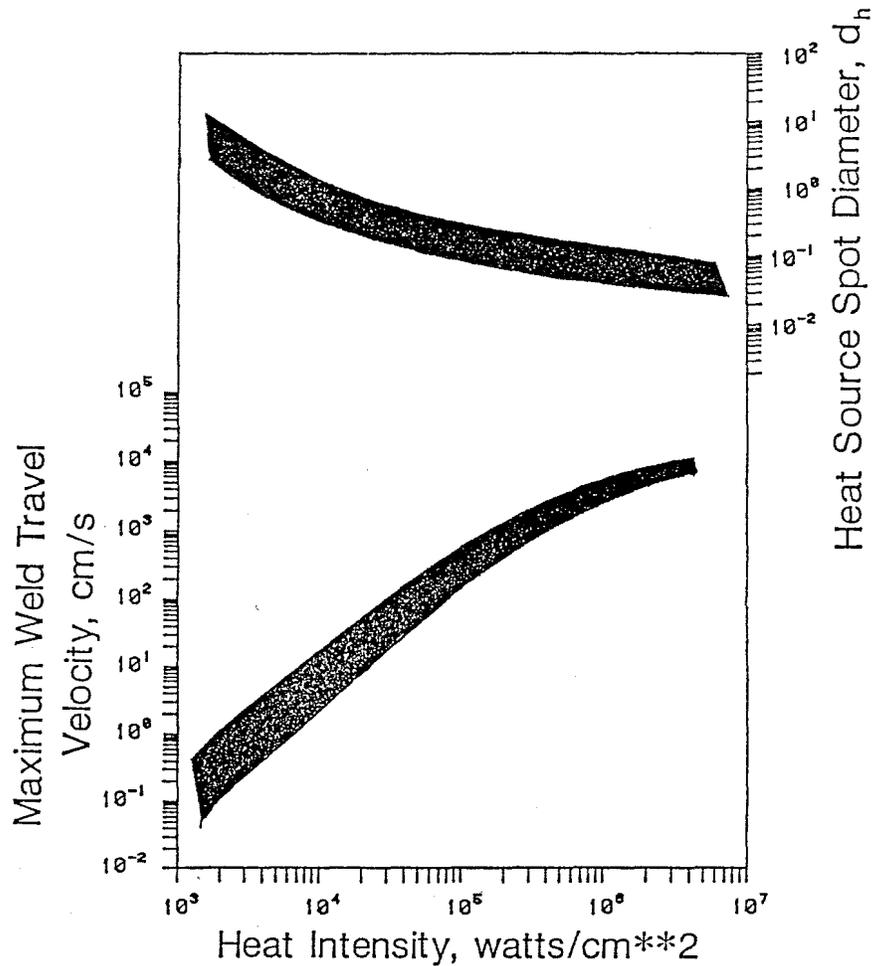


Figure 5

Typical weld pool-heat source interaction times as a function of source heat intensity. Materials with a high thermal diffusivity, such as copper or aluminum would lie near the top of this band, while steels, nickel alloys or titanium would lie in the middle, and uranium and ceramics, with very low thermal diffusivities, would lie near the bottom of the band.

Figure 6

Maximum weld travel velocity as a function of source heat intensity based upon typical heat source spot diameters.



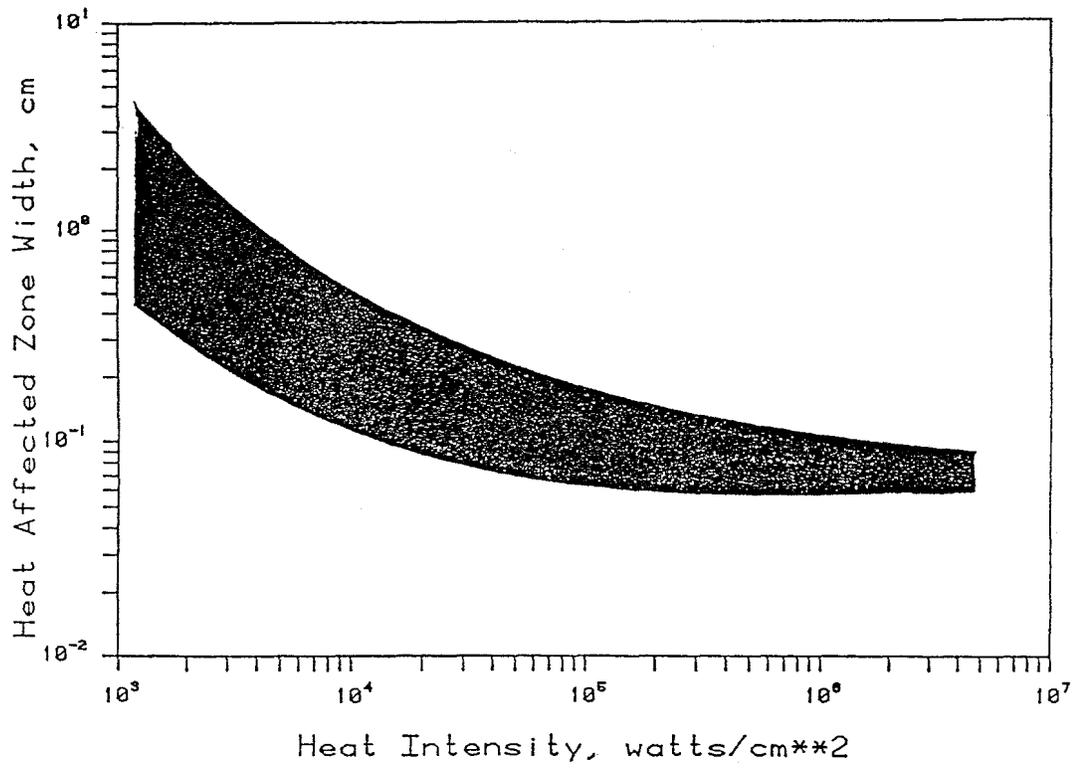


Figure 7

Range of weld heat affected zone widths as a function of source heat intensity.