Welding and Joining: Moving from Art to Science

New welding technology is often commercialized before a fundamental science emphasizing the underlying physics and chemistry can be developed

BY THOMAS W. EAGAR

Comfort A. Adams founded the American Welding Society (AWS) in 1919 to advance the science, technology and application of welding. Indeed, the Society is unusual in its breadth of approach to the field. Adams had seen the need for such breadth when he noted that: "There are two types of mind, the one trained in the routine technique of a manufacturing industry at that time, and the other which insisted on understanding the reason why, starting with a sound knowledge of the fundamental laws and phenomenon" (Ref. 1).

Thus, from the very beginning, Adams taught that there is a tremendous need, not only for those who apply the art or technique of welding, but also for those who seek to further the art through science. He realized welding is an extremely complex field, and wrote, "by that time, I was forced to realize that the science and art of welding involved so many branches of science that it had, as yet, a long way to go in the field of fundamental research" (Ref. 1).

An excellent review of the progress made in the science of welding over the first 40 years of the AWS was provided by C. E. Jackson in his 1955 Adams Lecture (Ref. 2).

Today, there is still a long way to go in the field of fundamental research in welding and joining. The pace of advancement of science and technology is quickening. A host of new materials, products and processes is continually being developed. There is a tremendous need to increase our research and development efforts, not only to improve upon the reliability, quality and cost of existing processes, but also to develop new processes. Fortunately, there is a way to increase our rate of progress in research and development.

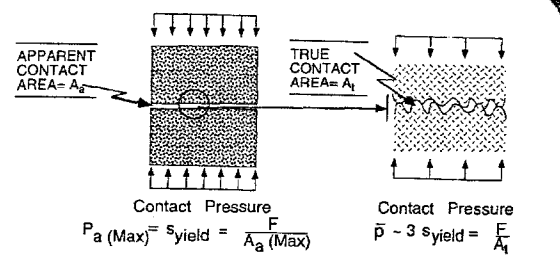
One of the greatest scientists of the 19th century, Lord Kelvin, taught us the secret of developing a successful scientific approach: "I often say that when you can measure what you are speaking about and express it in numbers, you know something about it; but when you cannot express it in numbers, your knowledge is of a meager 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."

Thus, Lord Kelvin reminds us that new ideas, thoughts or hypotheses must be confirmed by careful numerical analysis. Many learned people have developed conjectures about the "why" of a given process without attempting to test their theories numerically. As Kelvin suggests, failure to put numbers on our ideas leaves us with an art of welding, hard to measure and failing to progress to the science of welding. Today's technological advancements require that one evolve from the "art of welding" to the "science of welding." Kelvin teaches that the first step in developing a science is to be quantitative — Table 1. The second step, which J. Willard Gibbs, the father of modern thermodynamics, taught us, is that "One of the principal objects of theoretical research in any department of knowledge is to find the point of view from which the subject appears in its greatest simplicity" (Ref. 1).

To state it more simply, Albert Einstein quoted a Yiddish proverb, "As simple as possible but not simpler."

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The Maximum true area of contact is only 30% of the apparent area. Hence, high normal forces will not induce strong bonding.

Fig. 1 — Contact area during cold welding. A — Macroscopic; and B — microscopic.

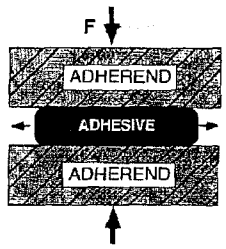


Fig. 2 — Adhesive bonding fundamentals, spreading of the adhesive.

Stefan Equation - Viscous flow of liquid between two parallel plates.

$$F \times t = k_\eta \left[\frac{1}{h_f^2} - \frac{1}{h_i^2} \right]$$

The viscosity of the adhesive controls the strength of the joint.

All scientific inquiry begins with an observation of the world around us. Anyone who asks the question "Why?" is a budding scientist. The next step in developing a science of welding and joining is "be observant" and look at the world in its simplest, not its most complex, form.

Welding and Joining Processes

Let us now take a few examples of how we can view various welding and joining processes in a simple yet quantitative way, consistent with the observations around us.

Cold Welding

Let's consider the principles of cold welding. Most people do not think of it as a common joining process, but in fact there are trillions of electrical contacts made every year by squeezing gold or aluminum wires onto the edge of silicon chips, thus attaching semiconductors electrically to the surrounding package.

To understand this process, we must observe it both macroscopically and microscopically. The macroscopically apparent area of contact is easily observed. This is the entire surface where the two objects come together. The greatest contact pressure would be equal to the macroscopic yield stress of the material as seen in Fig. 1.

Microscopically, on the other hand, we know that true contact is made only at local asperities. On a microscopic scale, every surface is locally very rough — Fig. 1. As these two surfaces come together, they contact only at the asperities.

It is also known from the principles of mechanics that due to triaxiality of the local stresses, the strength of these asperities is about three times greater than the yield strength of the material (Ref. 3). Since the total force squeezing the parts together is the same on both the macroscopic and microscopic scale, the true area of contact on the microscopic scale never exceeds more than about 30% of the macroscopic area, even when the two solids are pressed together to the point of deforming the material macroscopically.

Hence, by this simple analysis, it can be shown that more than one-third bonded area is never attained, no matter how hard you squeeze downward on any material.

It can be concluded that in order to achieve strong cold welds, we must develop interfacial shear across the joint, as such shear will deform the asperities and can result in 100% contact area. This simple analysis gives us a much greater understanding of a number of other joining processes including friction welding, ultrasonic welding and resistance welding.

Table 1 — Developing a Science of Welding and Joining

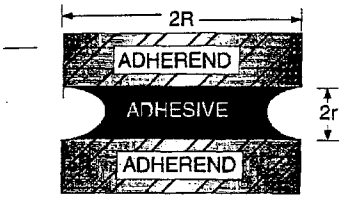
- ◆ Be quantitative
- ◆ Keep the analysis simple
- ◆ Be observant
- ◆ Be flexible in analysis method
- ◆ Be critical, question your assumptions
- ◆ Develop a holistic vision, new paradigms
- ◆ Blend both experiments and analysis

Adhesive Bonding

Another example of simple scientific analysis of a joining process comes from adhesive bonding. If there is a viscous adhesive between two solids, a force is required to cause the adhesive to spread across the joint. Joseph Stefan, an Austrian physicist best known for developing a law of thermal radiation, solved this problem over 100 years ago (Ref. 4). He found that the product of the force and the time that the liquid spreads equals a geometric constant, K, times the viscosity η, times the inverse of the final thickness squared, minus the inverse of the initial thickness squared — Fig. 2. This simple mathematical model of viscous flow between two solid plates shows that the strength of an adhesive joint is controlled primarily by the viscosity of the adhesive, and secondarily by the thinness of the joint. This equation leads one to consider how to alter the viscosity such that one starts with a low viscosity adhesive, which is easily spread across the joint, and later converts the adhesive to a very high viscosity so that a strong adhesive joint is obtained.

There are three basic ways to increase the viscosity of the adhesive. The first is solvent removal. This is essentially what you do when you lick a postage stamp. The saliva is the solvent that wicks away into the porous paper. As the solvent is wicked away, the adhesive rehardens, and the stamp sticks to the paper. Postage stamps do not stick well to glass surfaces because the glass will not absorb the solvent.

Another method of increasing the viscosity of an adhesive is polymerization. This is what happens in the mixing of epoxy cements. Combining the two chemicals allows them to form a three-dimensional polymer network that forms a stiff, strong glue. This is also what happens when we use "crazy" glue, which is a generic term for cyanoacrylate adhesives. In this case, it is the hydroxide molecules on the surface of the adherend that cause the glue to polymerize.

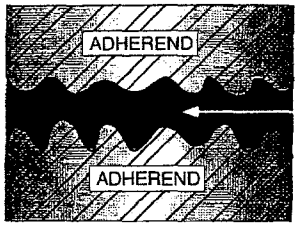


Pressure differential = Surface energy x Curvature

$$P_{adhesive} - P_{air} = \gamma_{LV}\left(\frac{1}{R} - \frac{1}{r}\right)$$

If r << R, the pressure difference is negative and the two objects are pulled together.

Fig. 3 — Fundamentals of adhesive bonding — Type I, surface tension adhesion.



This is the most common form of adhesive bonding and is the dominant mechanism in over 90% of the joints.

Fig. 4 — Fundamentals of adhesive bonding — Type II, mechanical interlocking.

You'll find that crazy glue works very well at sticking fingers together because human skin is slightly basic, whereas it works less quickly in bonding wood because the surface of wood is slightly acidic. If you were to paint the wood surface with a thin film of a caustic solution, the cyanoacrylate glue would work much faster.

Finally, a third mechanism for increasing the viscosity of the adhesive is to heat the adhesive and allow it to cool and solidify. Examples of this are hot melt adhesives, glue guns, or even the asphalt on the street.

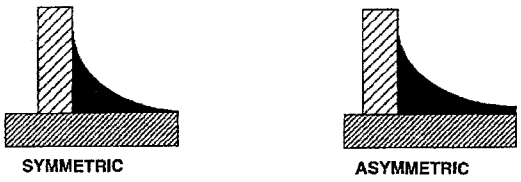
From this very simple, viscous flow analysis, we have a new way to understand the fundamental strength of adhesive joints. It is easily seen that by changing the viscosity, you can increase the force required either to form or to destroy the joint by 10 to 15 orders of magnitude. This is because the viscosity of a solid is 10 to 15 orders of magnitude greater than the viscosity of most liquids. You can increase the holding power by this tremendous amount by forming the joint with a low-viscosity liquid adhesive that later hardens to a high-viscosity solid. It is also seen that thinner adhesive joints will be stronger due to the inverse squared relationship of the final joint thickness.

Thus, it is seen that one way to quantify things is to develop some simple equations such as the Stefan equation. This allows us to determine the key parameters that control the strength of the joint, but there are additional ways to look at the science of adhesive joints.

It is known that the surface tension of a liquid can create a force of attraction between two solid adherends (Ref. 5). The wetting of the liquid with the surfaces creates a pressure differential between the air surrounding the material and the adhesive inside the joint. This pressure difference is given by the surface energy of the adhesive multiplied by the curvature of the liquid surface, as shown in Fig. 3.

If the thickness of the joint, which is approximately two times the radius of curvature of the adhesive in the thickness direction, is much less than the width of the adhesive, which is approximately twice the radius or curvature around the joint, the pressure difference is negative and the two objects are pulled together. This principle of adhesive bonding is easily seen with Johansen blocks. These blocks are two extremely smooth and flat metal surfaces which, when rubbed against the palm of the hand to pick up a little moisture and then rubbed together, will bond with significant strength. This is due to the wetting of the adhesive, which is merely the moisture from the hand. Because of the flatness and the smoothness of these Johansen blocks, the joint is extremely thin and a significant force is developed, holding the blocks together.

Another type of adhesive bonding, called Type II, is mechanical interlocking — Fig. 4. In this case, the adhesive fills the pores between the two solids and solidifies, thus holding or interlocking the pieces together. This is essentially the way that mortar holds bricks together in a building. In fact, this is the most common form of adhesive bonding and most likely is the dominant adhesion mechanism in over 90% of all adhesively bonded joints produced.



$$\text{Bond Number} = \frac{\text{Gravitational Force}}{\text{Surface Tension Force}}$$

$$\left[Bo = \frac{\rho g h}{\gamma / r}\right]$$

$$\text{If } r \approx h,\ Bo = \frac{\rho g r^2}{\gamma}$$

$$Bo = 1 \text{ when } r \cong 3\text{mm}$$

Fig. 5 — Symmetric and asymmetric fillet shapes formed with soldering.

Soldering

Another way to be quantitative without becoming overly complex is to look at the physics of a joining process by using dimensionless numbers. Dimensionless numbers are ratios of force, energy, mass, heat, length and time.

Using soldering as an example, we can understand why some solder joints form symmetric fillets, while others tend to sag and slump under the force of gravity, by developing a ratio of gravitational forces to surface tension forces acting on the liquid solder. Surface tension forces will tend to make a symmetric joint and gravitational forces will tend to form an asymmetric joint. By ratioing these two forces, a dimensionless number that other scientists have used previously is developed. This is called the Bond number, but its name has no relationship to joining. Mathematically, the Bond number is the gravitational force, ρgh, divided by the surface tension force γ/r. If the radius of curvature is also similar to the

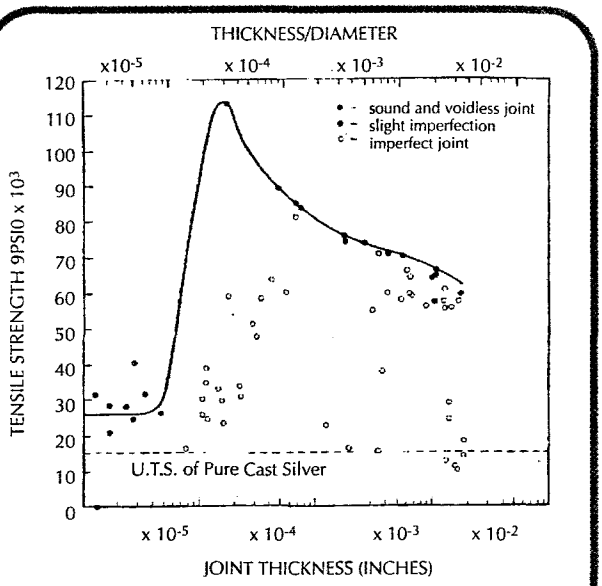


Fig. 6 — Tensile test results of brazing two pieces of steel using pure silver.

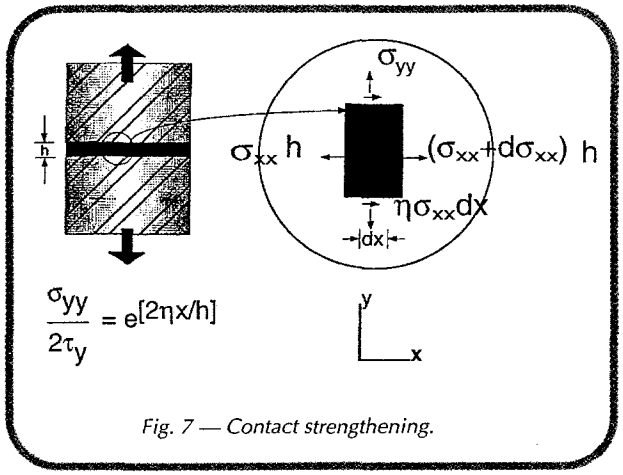


Fig. 7 — Contact strengthening.

height of the fillet, then the Bond number is $\rho g r^2$ divided by the surface tension — Fig. 5. It is found that when these gravitational forces and the surface tension forces are equal, or when the Bond number equals 1, the radius of a solder joint is approximately 3 mm. This is consistent with experimental observations in the literature (Ref. 6) wherein solder joints less than 3 mm in length are dominated by surface tension forces making them symmetric, while larger joints tend to sag due to gravity.

These examples illustrate another important principle in our development of a science of welding and joining. That is, one must be flexible in the method of analysis. There is no single technique that can be used to solve all problems, or as Maslow said, "If the only tool you have is a hammer, you tend to see every problem as a nail."

We must be flexible in our approach to these various problems. As Comfort Adams noted, "Welding involves many branches of science."

Each branch of science has its own techniques and skills. In some cases, one must be a physicist, in others, an electrical engineer, and yet in still others one must act as a mechanical engineer, a chemist or a mathematician. Indeed, the engineer must be broadly educated in science, able to seek out the most fruitful ways to approach problems and to solve them.

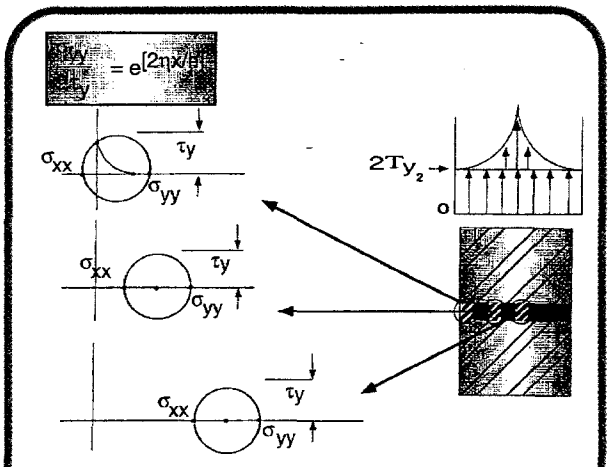


Fig. 8 — A Mohr's circle diagram showing contact strengthening.

Brazing

Consider the strength of a braze joint. It has been known for many years that the thinner the braze joint, the greater its strength (Ref. 7). Indeed, we find a very unusual result. That is, if the braze joint is thin enough, the mechanical properties of the joint are stronger than the braze material. In effect, the joint becomes stronger than its weakest link.

For example, Fig. 6 shows the results of brazing two pieces of steel using pure silver, which is very soft and does not have great strength. However, when we pull these joints in a tensile test, we learn that the joint can be stronger than the layer of silver that separates the two pieces of steel. As seen in Fig. 6, the strength of the joint can exceed the strength of the silver by sevenfold. This is called contact strengthening. Its origin is illustrated in Figs. 7 and 8. Consider the two pieces of material, steel with silver as a very soft interlayer. We can analyze the stresses around a small piece of the silver braze material. In analyzing these stresses, we can develop an equation that shows that the ratio of the yield strength of the joint to the shear strength of the silver follows an exponential relationship (Ref. 3). This is because as we move across the joint from the free surface, where the silver is relatively weak, into the center, triaxial stresses are introduced on the silver due to the nonyielding steel surrounding the silver. This is plotted mathematically on a Mohr's circle diagram in Fig. 8, which shows that the yield surface of the silver near the edge of the joint is relatively low. But, as we progress toward the center where the silver is restrained from movement by the nondeforming steel, the effective yield strength of the silver in the center is increased significantly. On average, the strength of the joint becomes significantly stronger than the strength of the silver.

We must be careful with this simple analysis of contact strengthening. The analysis is not yet complete. There are other types of loading such as impact, shear, fatigue, or corrosion loading that could cause this joint to fail at a much lower stress than could have been measured, either experimentally or theoretically, based on contact strengthening alone.

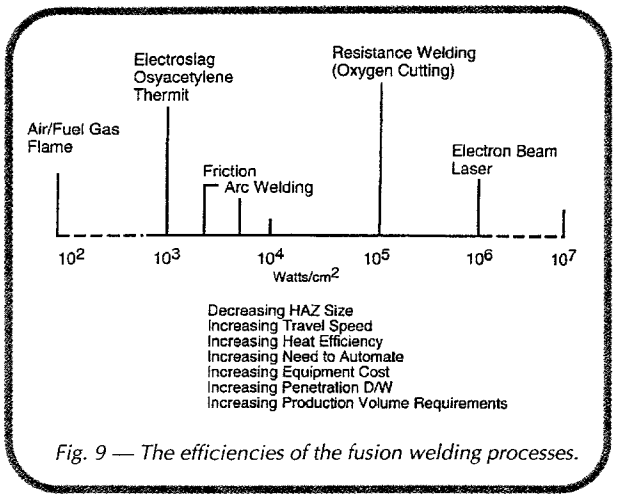


Fig. 9 — The efficiencies of the fusion welding processes.

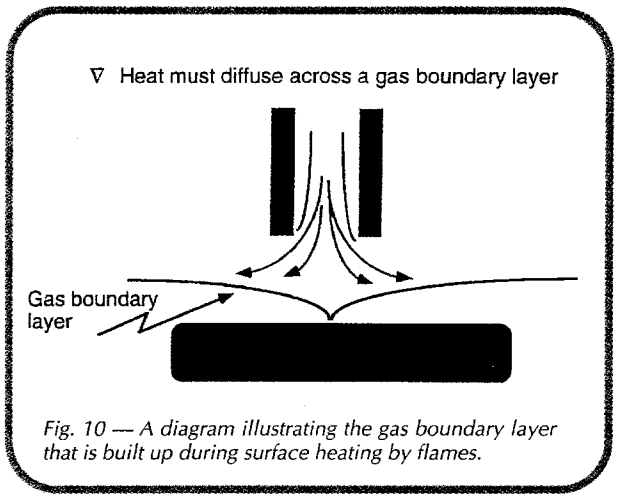


Fig. 10 — A diagram illustrating the gas boundary layer that is built up during surface heating by flames.

Nonetheless, since the approach is based upon sound scientific principles that have been quantified, we can predict the behavior of this joint under other conditions. That is one of the great strengths of the scientific approach. It allows one to be predictive. It must also be remembered, however, that the prediction is only as good as the assumptions of the simple model. Thus, it is not sufficient to be only quantitative and analytical. We must also be self-critical, always questioning our base assumptions.

Fusion Welding Processes

Fusion welding is one of the most frequently used welding processes. As we develop a quantitative understanding of these different welding processes, it is necessary to integrate this knowledge into a coherent, overall vision of the welding process. The breadth and complexity of the hundreds of joining processes require that we find new ways to help educate others about our current state of knowledge in a simple yet fundamentally correct manner.

One such example of a holistic paradigm that is very useful for viewing fusion welding is heat intensity. Fusion involves heating a material to its melting point, yet there are physical limits to the heating rate. If an energy of less than 1000 W/cm^2 is applied to the surface, most metals could conduct the heat away faster than it is put in, and the material would not melt. Thus, it is impossible to fuse metals with heating processes that produce less than 1000 W/cm^2 on the surface of the metal.

On the other hand, if the heat is applied to the surface at a rate exceeding 1,000,000 W/cm^2, the heat is introduced into the material so rapidly that it cannot possibly be conducted away through the material. The temperature of the surface increases rapidly such that the surface begins to vaporize. This is the higher end of the heat intensity scale. Processes that produce heat intensities above this limit do not create welds, but rather drill holes in the material (Ref. 8). Thus, all fusion welding processes must lie on this simple one-dimensional graph — Fig. 9. More important is that since this graph is fundamentally related to the physics of the process, one can relate it to a number of important features of the fusion welding process.

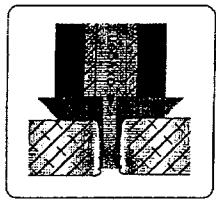
We find that as we move from the low end to the high end of the heat intensity ranges, there is a decrease in the heat-affected zone size of the weld from the order of a centimeter or more in width at one end, to a width of a millimeter or less at the other end. It is found as the heat intensity is increased, the maximum travel speed increases from a fraction of a cm/s to more than 1000 cm/s at high heat intensities (Ref. 9). In addition, the efficiency of heat utilization in the process increases from less than 10% at the left of Fig. 9 to nearly 100% at the right in terms of the melting efficiency.

We also find that as melting occurs at more rapid speeds, there is a need to automate the process. Indeed, the melting time for arc welding is on the order of a tenth of a second to a second. This is at the limit of the reaction time of a human. Faster welding requires mechanization. Thus, with reference to Fig. 9, manual welding can be done with oxyacetylene torches and arcs, but not with lasers, electron beams, or even resistance welding. These latter processes must be mechanized. This increases the equipment cost from approximately $1000 at one end of the scale to equipment costing as much as $1 million with all the necessary automation at the other end. The shape of the weld pool expressed as the depth-to-width ratio changes from approximately one tenth at one end of Fig. 9, to a factor of 10 or more at the other end. In addition, at the higher speeds more material is required to keep the machines busy. Indeed, laser and electron beams are extremely productive. They find their greatest application in the automotive industry where the volume of materials being processed is extremely high.

Thus, from this very simple diagram, which is related to the fundamental physics of the fusion welding process, we have a paradigm from which to predict the potential of new processes in terms of HAZ size, maximum travel speed, heating efficiency, equipment cost and automation, weld shape and production volume requirements.

Heating with Flames

Surface heating by flames is often characterized by a quantity known as the combustion index. This index is a measure of the rate at which heat is brought to the surface of the material. Since the heating of the surface is dependent upon both the temperature of the gas and the velocity at which the gas is brought to the surface (which is related to the expansion of the gas, which also is proportional to temperature), we find that the combustion index is related to the temperature squared. The difficulty is that when we estimate the theoretical combustion index, we calculate numbers that exceed the experimental values by a factor of 10 to 50. As Huxley said, "The great tragedy of science is the slaying



∇ The oxygen condenses as FeO

∇ No boundary layer is formed - therefore the measured combustion intensity equals the theoretical intensity -10^5 watts/cm^2

∇ The oxide of the metal should melt below the temperature at which the metal melts.

	T_{M_eO}	T_{M_e}
Fe	1380	1536
Al	2000	660
Mg	2800	650
Cr	2800	1875
Ti	1750	1668

Fig. 11 — In flame cutting, no gas boundary layer is formed.

∇ The combustion intensity is proportional to T^2

∇ The useful heat for melting steel is proportional to $[T_{flame} - T_{melt}]$

	Formula	Max. Flame Temperature	$[T_{flame} - T_{melt}]^2$
Acetylene	C_2H_2	3100°C	256 x 10^4
MAPP®	C_3H_4	2870°C	188 x 10^4

∇ For melting steel, acetylene has a 36 percent advantage

∇ For flame cutting, MAPP® has distinct safety advantages

Fig. 12 — MAPP gas vs. acetylene in the heating of steel.

of a beautiful hypothesis by an ugly fact."

This difference between theory and experiment can be reconciled by considering the physics of the process in a little more detail. The previous model was too simple in that it neglected the fact that when a gas strikes the surface of the material, it builds up a boundary layer or insulating gas layer next to the surface. Thus, the heat developed in the flame must diffuse across this boundary layer before it reaches the material being heated. It is the creation of this boundary layer that limits our ability to heat materials with flames — Fig. 10.

This boundary layer principle is also very important in the process of arc welding. With arc welding, one can increase heat transport to the surface from the plasma flame of the arc by passing a current through the arc. The electrons do not need to diffuse across the boundary layer, but are transported rapidly across it (Ref. 11).

By comparing the heating process of a flame with the heating process of an arc, we find that 90% of the heat of an arc is carried by the electron flow and hence, a tenfold increase in the heat intensity with arcs as compared with flames is achieved. The limitation of the boundary layer is avoided by introducing the flow of the electron across the layer.

Not only does this simple boundary layer model help explain heating by flames, but it helps explain arcs as well. By extension of this analysis, it is found that the temperature of the arc is relatively unimportant in determining the heating efficiency of arcs (Ref. 12).

Another way we can expand upon the understanding of boundary layers relates to flame cutting. In this process, a cold oxygen gas strikes the hot metal surface — Fig. 11. The speed at which metal can be cut with oxygen flames indicates that heat intensifies 10 to 50 times the heat that is generated by a simple flame. The reason for this is that as the oxygen in the gas meets the hot iron of the workpiece surface, it condenses the boundary layer of oxygen gas into a liquid iron-oxide. Hence, no gas boundary layer is formed and the measured combustion intensity equals the theoretical intensity, which is on the order of 10^5 W/cm^2.

The flame cutting process must also have an oxide that is molten and that can be blown aside by the incoming gas jet. This requires that the metal have an oxide that melts below the melting point of the metal. This is true for iron, but aluminum cannot be flame cut because the melting point of aluminum oxide exceeds the melting point of aluminum. Magnesium or chromium cannot be flame cut for the same reason. Chromium, an important component in stainless steels, inhibits the flame cutting of these metals. The only exception to this rule of a lower melting oxide than the base metal when flame cutting is titanium, which has a very similar melting point of the oxide and the metal. However, titanium dissolves its own oxide so readily that the oxide that is formed is carried away by diffusion into the titanium, exposing fresh titanium metal to react with the incoming oxygen jet. Thus, these simple models have helped to explain why some metals behave differently than others during flame cutting.

One can also compare the behavior of different gases. Methylacetylene-propadiene (MAPP®) and acetylene gases are important fuels in the industry. There is often a debate as to which is better as a fuel gas for a given application — MAPP or acetylene. Remembering the earlier discussion that the combustion intensity of a flame is proportional to the temperature squared, the useful heat for melting of steels is proportional to the flame temperature minus the melting temperature of the steel, since there is no melting until the melting temperature is exceeded. Using these two simple facts and applying them to acetylene and MAPP gases, one can calculate the theoretical maximum temperature for each of these flames, and then square that difference between the flame temperature and the melting temperature of the steel — Fig. 12. In doing this, we find that for melting steel or oxyfuel welding, acetylene has a 36% advantage over MAPP. However, for flame cutting where the rate of heat transfer is not a limitation, MAPP gas has distinct safety advantages over acetylene.

Heat Flow

Heat flow is one of the most basic physical phenomena in all fusion welding processes. For this reason, there are literally thousands of technical papers on the subject. With the advent of ever-more-powerful computers, we can calculate the details of heat flow during welding more precisely than it can be measured; however, the more we learn about the details of heat flow during welding, the more we find that nearly all of the practical problems concerning heat flow can be solved with reference to one simple quantity — the Fourier Number, which is stated as:

$$\frac{X}{\sqrt{\alpha t}} = \frac{\text{Distance}}{\text{Thermal Diffusivity x Time}}$$

This simple quantity, which relates the distance that heat travels to the product of thermal diffusivity of the material

and the time, can be used to solve 98% of all practical heat flow problems in welding. If the Fourier number is much greater than one, the material is relatively thick and heat flow is limited by thermal diffusivity. If the Fourier number is much less than one, the material is relatively thin and thermal gradients will be small. If the Fourier number is nearly one, it may be necessary to perform a more complex heat flow analysis.

Heat flow analysis is one of the few areas of welding where the scientific knowledge has outstripped our need. There is a tremendous amount of scientific welding talent being wasted in pursuing mathematical games involving heat flow. Studies refine the third and fourth significant figures of a process for which there is still inadequate physical understanding beyond the first or second significant figures. Playing games on the computer is not science. One should remember the warning of Norman Augustine: "Software is like entropy. It is difficult to grasp, weighs nothing, and obeys the Second Law of Thermodynamics; that is, it always increases" (Ref. 13).

Our challenge is to develop greater physical understanding of welding and joining processes, not to develop elaborate mathematical formulations that serve no practical purposes. There are hundreds of other examples of how to quantify welding processes that cannot be presented in this paper. It is hoped that others will continue to contribute their insights concerning welding processes, no matter how simple. As long as the correct physics is included, the simpler analysis is the better analysis from the point of view of developing a science of welding.

Finally, it is also essential to blend both experiments and analysis. Theories must be tested against the reality of the world, otherwise they are only hypotheses.

Conclusion

The field of welding and joining has progressed markedly during the 76 years since the American Welding Society was formed, but the rate of progress must increase if we are to keep pace with the rapidly advancing technology around us. This can be done if the approach emphasizes simple, quantitative explorations that contain the essential physics of the process. Unfortunately, too much effort is often spent on refining existing analyses with even more sophisticated mathematics. While this does demonstrate mathematical proficiency, it does not advance the field of welding and joining very far. It is necessary to step back and critically question what is known and why it is known. A wise man once said, "It is not what I don't know that will hurt me; it is what I know for sure, that is not true, that will cause me harm." Only by quantifying our hypotheses and by testing them experimentally can we hope to progress as rapidly as we must. ◆

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