Welding in the Digital Age

A professor asks young people to choose a career in welding engineering

BY TARASANKAR DEBROY

Is becoming a welding engineer a good career choice today? Welding is at the heart of many great engineering achievements. It is essential for mechanization of agriculture, generation of energy, distribution of clean water, and production of medical devices. True, in this digital age, self-driving cars, robots for remote surgery, and other products of emerging technologies seem more exciting. But, today's dizzying pace of progress in engineering often merges the time-tested mature fields such as welding with the new fields like digital data processing into a powerful stream for the benefit of all people.

Welding today is much more advanced than it was just a few decades ago, and I hope this article will help you make an informed career choice.

From about 3000 welds in a car to numerous joints in large buildings, bridges, and other important structures (Fig. 1), welds are everywhere. Transportation, manufacturing, electronics, and other industries that support our standard of living depend on it. Welding-related expenditures by these industries in the United States were about $34 billion in 2000, which was about one tenth the cost of all cars sold annually.

While the joining of metals has been practiced since prehistoric times, modern welding technology began after electricity became available in the 19th century. Since then, both its engineering practice and the underlying scientific knowledge base have matured. Today, structurally sound and reliable joints of numerous engineering alloys, including many that were previously considered difficult to weld, can be made with confidence.

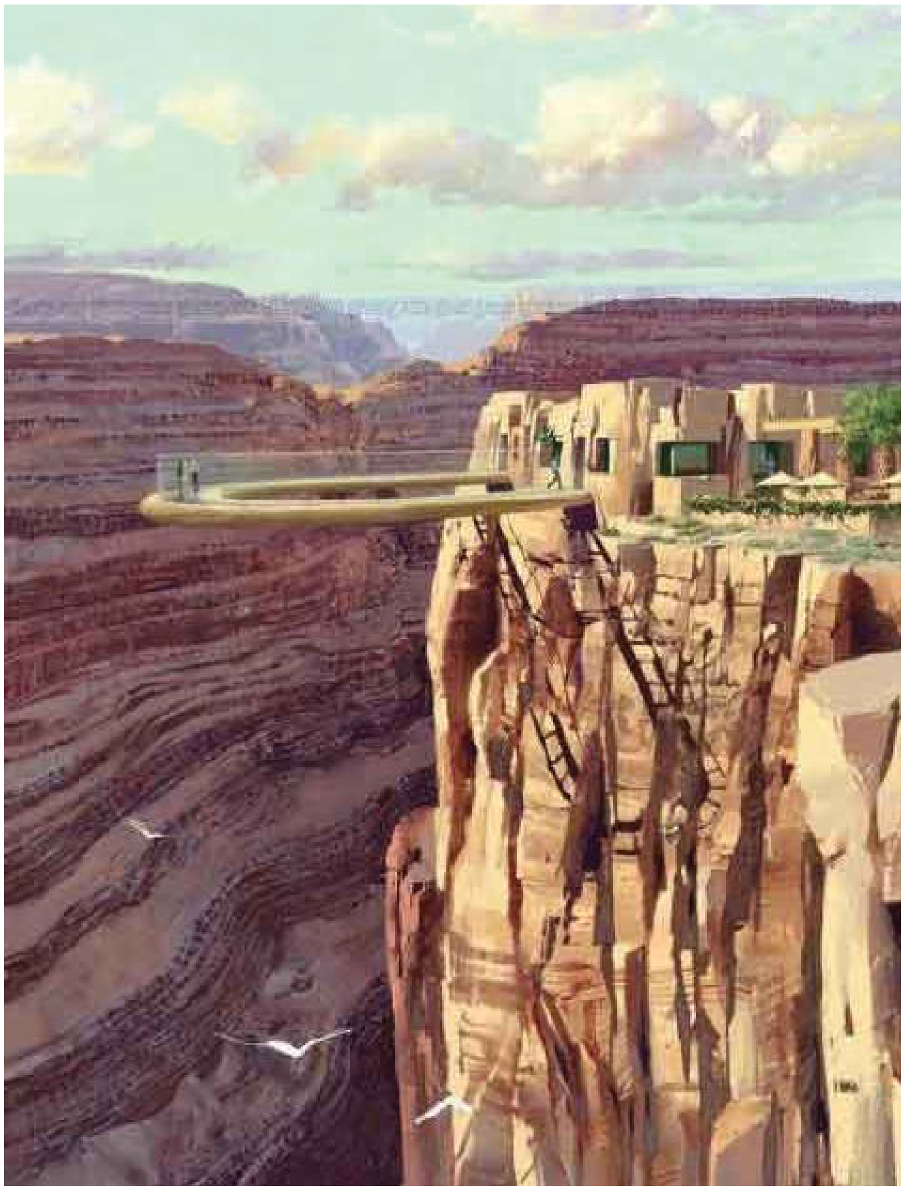

Fig. 1 — The stunning Grand Canyon Skywalk was built with round-the-clock welding in 10-h shifts. Designed to withstand large earthquakes, this huge structure consists of three steel plates, 3200 lb each. The structure houses a 3-in.-thick, heat-strengthened glass walkway (Ref. 1).

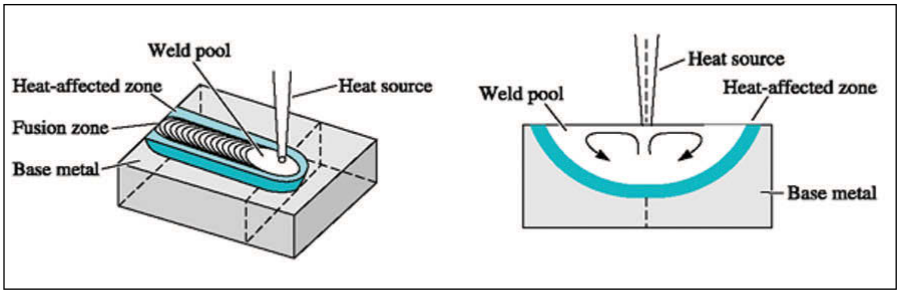

Fig. 2 — A schematic of the fusion welding process is shown at left and a transverse cross section, perpendicular to the direction of welding, is shown at right (Ref. 2).

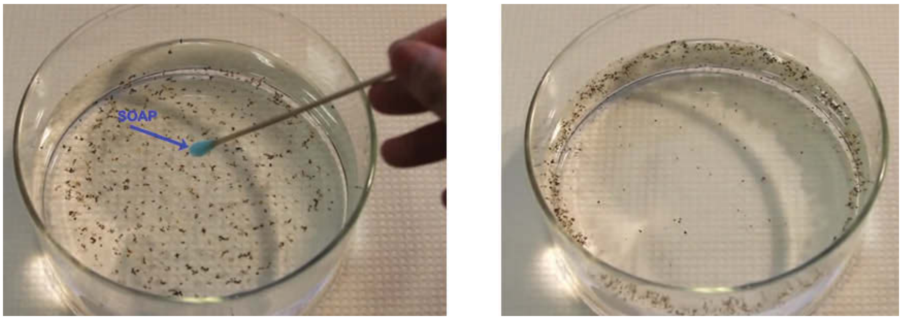

Fig. 3 — The photo on the left shows pepper on the water's surface and a cotton swab that was dipped in soap. The photo at right shows the pepper moves away from the center after the swab is dipped into the water (Ref. 3).

Because of its close connection to construction projects, many view welding as a primitive and dangerous art. At any sizable construction site, sparks fly, fumes spread their musty aroma, and large skull and crossbones warning posters speak volumes about welding's hazards. However, the reality is very different from the perception. The welding industry has an excellent safety record, robots now perform many of the repetitious and difficult tasks, and a mature and sophisticated scientific knowledge base supports welding practices. Most exciting, since the 1970s, the expanding digital data processing capabilities have been combined with the well-established technological knowledge base of welding, totally transforming both its practice and the underlying analytical capability that supports it.

Analytical capability is important for problem solving because problems in welding often affect life and property. This article focuses on uncovering a long-standing mystery in welding that remained elusive until the tools of the digital age were used. In a larger context, it shows how the renaissance brought about by the fusion of mature and new technologies has taught engineers powerful lessons while providing significant benefits to all people.

A Welding Primer

As you likely know, the purpose of welding is to combine two parts — metallic materials in most cases — into a strong joint. Several common terms used in describing different regions of the weld are shown in Fig. 2 (Ref. 2). In fusion welding processes, the joint forms by the melting and solidification of the metal parts. The region under the heat source melts forming a liquid metal puddle called the weld pool. A small solid region next to the weld pool, where the structure and properties of the workpiece are changed by heat, is called the heat-affected zone (HAZ). The size and shape, or geometry, of the weld pool is affected by how much heat is absorbed and distributed within it. Temperatures vary within the weld pool, and heat flows by conduction from high to low temperatures and by convection from the motion of the hot liquid metal.

The molten metal within the weld pool circulates under the action of several forces. The most important, Marangoni force, is named after Italian scientist Carlos Marangoni, who showed that liquids move from regions of low to high surface tension. The nature of this force can be easily understood from the motion of pepper in water — Fig. 3. When a cotton swab dipped in household soap is immersed in water, the pepper moves away from the swab (Ref. 3) (Fig. 3, right). Adding soap to water reduces its surface tension locally. Water flows away from the low surface tension region to where the surface tension is relatively high (Ref. 3). A similar effect causes weld metal to flow within the weld pool. Surface tension of the weld metal depends on temperature. So its value just under the heat source is different from that in other regions and this difference drives the flow of weld metal.

The gravitational force tends to sink the colder, heavier liquid near the edge of the weld pool and raise the hotter, lighter liquid metal in the middle of the weld pool. In addition, during arc welding, an electromagnetic force is generated from the interaction between the current path in the weld pool and the magnetic field it generates. Of these three forces, the gravitational force is by far the weakest, and during arc welding, the electromagnetic force is comparable to the Marangoni force only at fairly high currents. In most cases, the Marangoni force provides the main driving force for the flow of weld metal within the weld pool. The rolling streams of weld met-

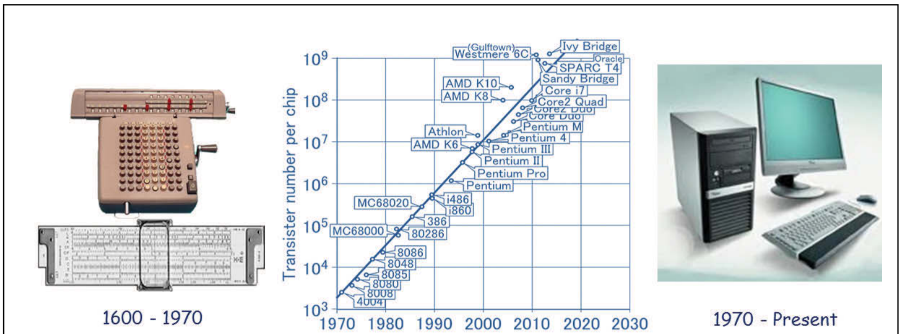

Fig. 4 — Progression of computational hardware from mechanical to digital devices.

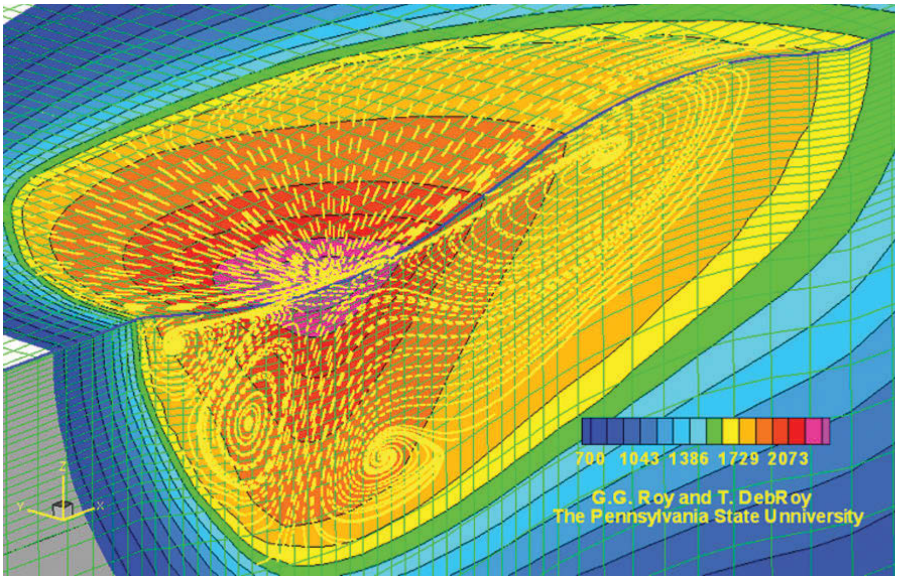

Fig. 5 — Computed flow of weld metal during arc welding. The colors represent temperatures in K and the dotted lines represent the lines of flow of liquid. The two loops shown near the surface are from the Marangoni flow and the two loops below the surface result from electromagnetic force (Ref. 4).

al carry heat from underneath the heat source to all other locations within the weld pool. Its circulation determines the melting pattern of the various regions of the workpiece, the shape and size of the weld pool, and the structure and properties of the welded joint. But the weld metals are opaque and very hot. As a result, the actual velocities and temperatures within the weld pool have not been experimentally measured so far.

A welcome recourse emerged in the 1970s. Advancements in computer hardware and software (Fig. 4) made fluid flow and heat transfer calculations accurate and affordable. Engineers now routinely use these calculations in critical designs in aeronautical, aerospace, civil, and other engineering disciplines. In welding, there are many important problems that cannot be solved without these calculations, at least not easily.

Billions of Equations Solved Instantly

Evolution of computational hardware and software from mechanical to analog to digital calculations has improved both the theory and practice of welding. The combination of digital computers and robots has improved joint quality, enhanced safety, and taken the boredom out of repetitious welding in automotive and other industries. Clearly, a new manufacturing paradigm has emerged. What is less apparent but equally important is the advancement of analytical ability for problem solving and design based on fundamental principles.

There are compelling reasons for detailed understanding of heat transfer and fluid flow in welding. Both the temperatures and velocities at all locations in the weld pool affect not just its shape and size, but the mixing of the filler metals, cooling rates at different locations, vaporization of alloying elements, weld metal composition, and the structure and properties of the joint. Local temperatures and velocities can be calculated by solving equations of conservation of mass, momentum, and energy (Ref. 4). Since these equations are too complex to be solved analytically, an appropriate numerical method is needed. A typical numerical solution procedure starts by dividing the workpiece into many small volumes or cells, typically about 250,000 cells. For each cell, an algebraic equation relates the local values of a variable with its values at the neighboring cells (Ref. 5). Typically, the variables include three components of velocities, enthalpy or temperature, and pressure, which are solved repeatedly until correct solutions are obtained. For these five variables, a total of 5 × 250,000 or 1.25 million equations have to be solved for each attempt at solution, commonly called an iteration. In most cases, several thousand iterations are needed before correct solutions for the variables at all cells are obtained. So, several billion equations are solved cumulatively to get temperatures and velocities in the entire workpiece. Today, about a billion such linear algebraic equations can be solved in about two minutes using inexpensive laptops.

Typical computed temperature and velocity fields during gas tungsten arc welding are shown in Fig. 5. The figure shows regions of different temperatures by specific color bands. Since the heat source is moving, the temperature changes rapidly in the cold workpiece ahead of the moving weld pool. Behind the weld pool where the material has already been heated, the metal cools slowly in air and the temperatures change more gradually. On the weld pool surface, liquid metal moves away from the low surface tension region under the heat source to other regions where the surface tension is higher. The surface is depressed below the arc because it exerts pressure on the liquid surface and forms a small hump behind the arc. The velocities range from a few tens of centimeters per second to about a meter per second, and the liquid metal carries a significant amount of heat from under the heat source to all other locations within the weld pool.

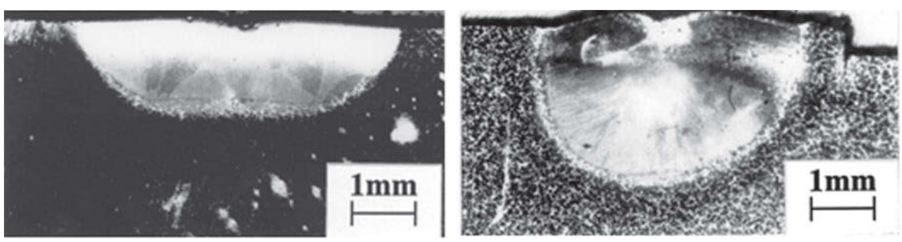

Fig. 6 — Weld cross sections of 15-mm-thick, high-speed steel plates containing 0.9%C, 3.9%Cr, 6.3%W, 4.8%Mo, 1.8%V, 4.6%Co, 0.2%Mn, 0.5%Si by weight containing 20 ppm sulfur (left) and 150 ppm sulfur (right) spot welded at a laser power of 5200 W for 5 s (Ref. 11).

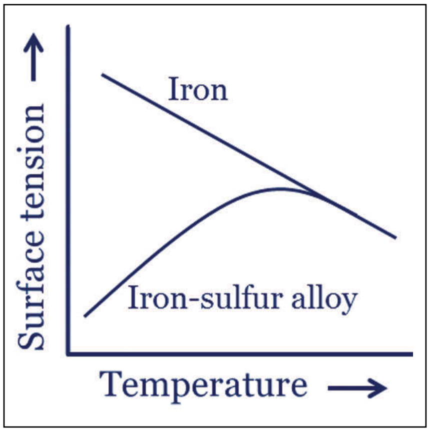

Fig. 7 — Variation of surface tension with temperature (Ref. 12).

An Enduring Mystery

The Puzzle and Its Importance

Failure to reproduce experiments is unacceptable in science and so, when the same grade of steels are welded under the exact same welding conditions, it would be absurd to expect weld-to-weld variations in geometry. In reality, this totally unexpected behavior was the norm when the same grade of steel with minor variations in composition was welded (Refs. 6–10). Figure 6 shows cross sections of two welds fabricated using the exact same procedure from the same grade of steel that are strikingly different (Ref. 11). The main difference in the steels was the amount of sulfur, which differed by 130 parts per million (ppm) by weight. Finding a solution to this long-standing puzzle (Refs. 6–10) was important because the weld geometry affects its performance; however, the solution remained elusive for decades (Refs. 8–10).

A Promising Hypothesis

A team of scientists at the Rocky Flats plant, a former nuclear weapons production facility near Denver, Colo., (Refs. 8–10) first presented a promising solution to this mystery in the early 1980s. They proposed a hypothesis to explain why a small amount of selenium (Ref. 6) or sulfur (Ref. 7) in steel significantly increases the depth of penetration.

They considered how sulfur affects the surface tension of liquid steel, weld metal spin, convective heat transfer, and the resulting weld pool geometry. Figure 7 shows the surface tension of pure iron decreases with temperature. The same trend is observed for steels (very low sulfur). However, when a small amount of sulfur is present, the surface tension decreases overall and increases with temperature as shown in the figure. At temperatures close to the boiling point, the surface tension decreases with increase in temperature. Sulfur and many other alloying elements such as oxygen, nitrogen, selenium, and tellurium have a tendency to migrate to the surface of the liquid steel. They all affect the surface tension in a manner similar to sulfur and are called surface-active elements (Ref. 12).

Directly under the heat source, the liquid metal has the highest temperature and lowest surface tension when the steel contains practically no sulfur. Since liquids flow from low to high surface tension regions, hot liquid steel moves sideways from the middle to the edge of the weld pool and melts metal there. It then turns downward as shown in Fig. 8A. As a result, the weld pool becomes wide and shallow.

Small additions of sulfur change the flow pattern completely. Hot liquid under the heat source now has a higher surface tension than that in the cooler regions — Fig. 7. So, on the surface of the weld pool, the weld metal rushes to the middle then moves downward to the bottom of the weld pool. The downward flow of the hot metal in the middle of the weld pool works like a thermal drill and a deep weld pool forms, as shown in Fig. 8B. The Rocky flats team also showed that selenium affected the shape of the weld pool just like sulfur.

The hypothesis the Rocky Flats team proposed provided a plausible explanation. However, in order for their theory to gain traction, direct proof of changes in the flow of liquid weld metal was required. Since metals are opaque and the liquid weld metal is very hot, this was not an easy task. They added some tiny alumina particles that floated on the surface of the weld (Ref. 9) and used a high-speed camera to film their motion during welding. The evidence was now at hand. Sulfur does change the flow pattern of liquid metal (Ref. 9). Insightful and elegant, their work inspired many other researchers.

Helpful but Incomplete

The work at Rocky Flats explained why a small amount of sulfur or selenium changed the shape of welds for the conditions of their welding. But after more than a decade, when experiments were conducted to cover more extensive welding conditions, it was found that sulfur does not always change the shape and size of the weld pool, although it does so in many cases (Ref. 11). So, the mystery actually deepened. The powerful spark of a new idea incubated at the Rocky Flats plant still required more work for a deeper understanding of when sulfur changes the shape and when it does not, and why.

The Rocky Flats team explained the role of selenium and sulfur assuming convection as the mechanism of heat transfer. This mechanism, valid only when velocities within the weld pool are large, was indeed valid for their experiments. However, the assumed convective heat transfer mechanism is not always valid, because the velocities are small for certain welding conditions. A rigorous understanding of the role of surface-active elements for a specific welding condition requires mechanistic insight of heat transfer achievable through a combination of experiments

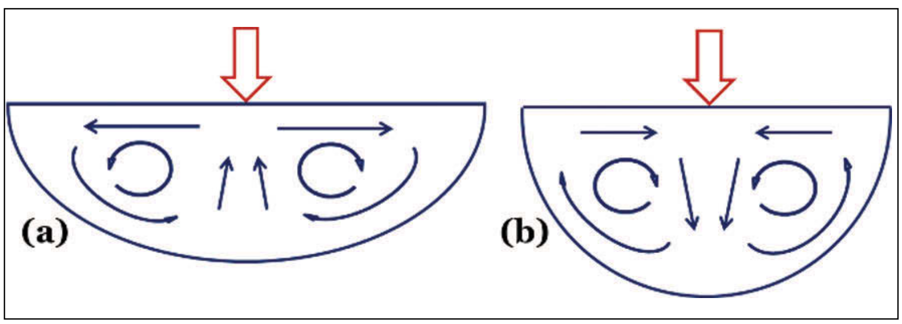

Fig. 8 — A — Pure iron flows sideways from the middle, making the weld pool wide and shallow; B — when a small amount of sulfur is added, the alloy goes downward in the middle of the weld pool resulting in a deep weld pool.

and mathematical modeling.

The first computational study (Ref. 13) of the effects of surface-active elements in welding was published by a team at MIT in 1983 that investigated convection in arc weld pools. They showed that, in many cases, the surface tension driven flow dominates the convection in the arc weld pool. But more important, they also proved that a small amount of sulfur or selenium influenced the direction and magnitude of the liquid metal flow, a behavior the Rocky Flats team observed experimentally. These calculations, with assumed weld pool shape and size, were a giant step forward because they provided a world of insight that could not be obtained by any other means.

Only the Numbers Reveal the Whole Truth

The influence of selenium or sulfur depends on the mechanism of heat transfer which, in turn, is determined by the magnitude of the velocities and the thermal conductivity of the liquid metal. If the velocities are small for the conditions of welding, the direction of liquid metal circulation does not affect the shape of the weld pool. As a result, sulfur and other surface-active elements do not always affect the weld pool shape.

Only comprehensive computer simulations can reveal the velocity fields and the mechanism of heat transfer. Such calculations show when surface-active elements affect weld pool geometry and when they do not. Two welding experiments and their computer simulations are presented here to show how the same level of sulfur may or may not affect the weld pool geometry depending on the welding conditions.

A side by side comparison of experimentally determined and numerically computed weld pool cross sections (Ref. 11) of two high-power laser spot welds of steels is shown in Fig. 9. For a sulfur content of 20 ppm, calculations show a strong convection current transports liquid metal from the middle of the weld pool sideways. The surface velocities are fairly large, on the order of about 20 cm/s, and at this velocity, convection is the main mechanism of heat transfer. In comparison, heat transfer by conduction is negligible (Ref. 11). The molten metal flows sideways from the middle, forming a shallow weld pool, as shown in Fig. 9A.

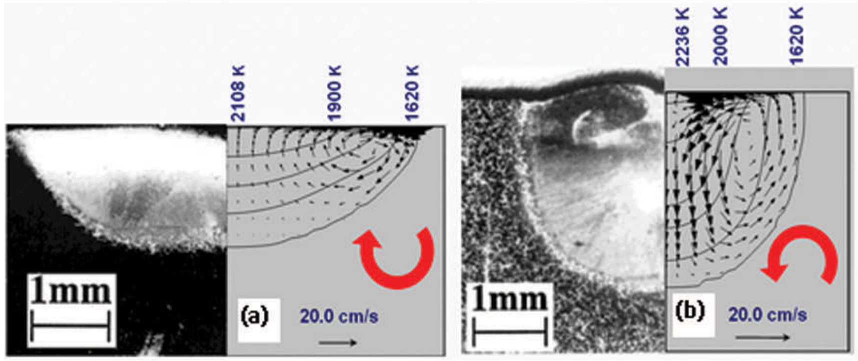

Fig. 9 — Experimentally determined and theoretically calculated weld pool geometries in a 15-mm-thick, high-speed steel plate spot laser welded for 5 s. The welds had 20 and 150 ppm sulfur on the left and right sides, respectively (Ref. 11).

When the sulfur content is 150 ppm, the circulation pattern is opposite to what was observed for the 20 ppm sulfur steel weld shown in Fig. 9B. The surface velocities are fairly large, higher than 20 cm/s. So the heat is carried mostly by convection, and conduction heat transfer is unimportant (Ref. 11). Hot weld metal flows downward under the heat source, the base metal melts near the root, and a deep weld pool forms. The computed weld pool geometry agrees well with the experimentally determined geometries in both cases.

But sulfur does not always change the weld pool geometry (Ref. 11). Figure 10 shows no perceptible difference in the cross sections of low-power laser welds in steel containing 20 and 150 ppm of sulfur. The numerical simulation of heat transfer and fluid flow reveals why.

The computed results show fairly low peak temperatures and lower velocities in the weld pool for these small welds. Convection did not carry much heat since the velocities in both cases were weak. As a result, conduction was the main mechanism of heat transfer. The direction of spin of the weld metal was opposite in the two cases as expected, but since conduction was the mechanism of heat transfer, the opposing spin did not result in any difference in geometry (Ref. 11). The mechanism of heat transfer was the most important factor, not the concentration of sulfur or the direction of weld metal spin.

Dramatic effects of sulfur, selenium, and other surface-active elements known for many decades led many to believe these elements always affected weld pool geometry. In fact, only when convection is the dominant mechanism of heat transfer can the surface-active elements play an important role in affecting weld geometry.

Solving a compelling problem of lack of reproducibility of the weld geometry has made the world a safer place for all people. But does the innovation and discovery stop once a long-standing mystery is solved? Not at all, because new welding problems that affect life and property arise frequently. The following example shows that the

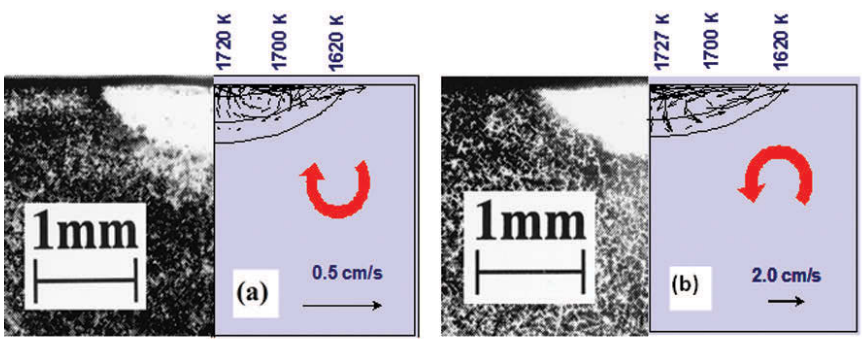

Fig. 10 — Comparison of the computed and experimental weld pool geometries at a laser power of 1900 W for steels containing A — 20 ppm; B — 150 ppm sulfur (Ref. 11).

powerful tools of the digital age can accelerate the pace of solution and help in producing reliable and better-engineered welds.

Sulfur Strikes Back

When each half of the joint contains steels with significantly different concentrations of sulfur, a totally unexpected result is observed. Since the arc is positioned just above the original joint of the two plates, it is expected that both plates melt equally. Instead, melting occurs mainly in the low-sulfur plate (Ref. 14) — Fig. 11. The point of maximum penetration, B, is laterally shifted from the location of the original joint, A. The figure shows the weld bead has clearly shifted toward the plate with lower sulfur content.

The extent of shift depended on the difference between the sulfur concentrations of the two plates and the heat input per unit length (Refs. 14, 15). Furthermore, the arc was asymmetric with a flare toward the low sulfur side (Ref. 15). To examine the role of arc flaring and the Marangoni convection, experiments were also done with a laser beam to avoid the effect of arc flaring (Ref. 16). Pronounced centerline shift and selective melting of the low-sulfur steel were still observed when a laser beam was placed directly above the original joint interface. Numerical modeling established that Marangoni convection was an important factor in transporting metal from high- to low-sulfur steel, which caused selective melting of the low-sulfur plate (Ref. 14). A pronounced rotational asymmetry (Ref. 16) of the weld bead during laser welding of steels with dissimilar sulfur concentrations was also observed. A mechanistic understanding of the rotational asymmetry still remains to be developed (Ref. 17). So, the enduring mystery of the surface-active elements still persists in a different form.

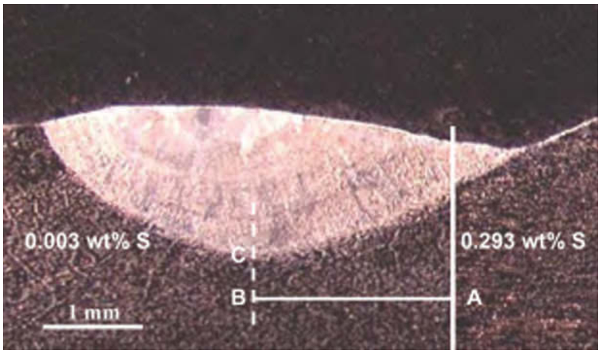

Fig. 11 — Weld geometry when welding two stainless steel plates with different sulfur contents. The white vertical line passing through point "A" indicates the original interface of the two plates. The location of maximum weld penetration is indicated by point C, and AB indicates the shift of the maximum penetration from the original joint of the two plates (Ref. 14).

Welding Engineering as a Career

The welding mystery described here shows the diversity of scientific subfields within welding engineering. Many of today's welding engineers have academic degrees in metallurgy and materials, mechanical, electrical, and several other branches of engineering. But a degree is just the beginning. From heat transfer to robotics, computers, control theory, corrosion, materials performance, and properties, there are many technical areas of opportunity for lifelong on-the-job learning.

Highly sought after in the automotive, aerospace, construction, energy, shipbuilding, electronics, and appliance industries, welding engineers perform many important tasks. Welding process selection, quality control, code compliance, and design of hardware and software are just a few examples of the crucial tasks for welding engineers in diverse activities ranging from underwater construction to numerous manufacturing processes to building a spaceship. Some welding engineers work in research and development in universities, national labs, and industrial labs to solve problems and advance the knowledge base that supports the practice of welding.

After four years of engineering college, you will be among a highly select group of people, much smaller than 1% of the population, with technical skills that are essential in today's world. If you select the fascinating field of welding engineering as a career, you will have an awesome opportunity to assimilate new contemporary technologies into welding and improve our world in numerous ways. Better welding can build more reliable machinery for better agriculture, housing, energy, clean water, transportation, health care, and practically all equipment that support our standard of living. I hope you will consider the exciting field of welding engineering as a career. WJ

Epilogue and Lessons

Synthesis of the knowledge base of a mature and important field such as welding with the emerging awesome digital data processing capabilities has helped in the production of better welds and made the world a better place. Apart from more rigorous analysis and solution of complex problems, the synthesis of welding and computational capabilities has also incubated a transformative new technology. Additive manufacturing, which has been hailed as the future of manufacturing, evolved from this merger. It starts with a digital picture of a part in a computer and builds it by adding liquid metal, layer by layer. Machines that use an electron beam welding gun and deposit 7 to 20 lb of metal per hour to make large parts are already available (Ref. 18). This disruptive additive manufacturing process is an example of welding's evolution in the digital age and proof that better welding can build a better world for all.

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TARASANKAR DEBROY (rtd1@psu.edu) *is professor, Materials Science and Engineering, Penn State University, University Park, Pa.*