PUTTING IT IN SCALE

A new series of algorithms aims to achieve some of the intuitive skills of veteran engineers.

By Patricio F. Mendez, Stuart B. Brown, and Thomas W. Eagar

IF AUTOMATIC WELDING SPEEDS COULD BE INcreased by 10 percent, the world would save hundreds of millions of dollars in productivity. Beyond a certain welding speed, though, defects appear in the weld, and the weld no longer looks like a thick, continuous seam. Instead, it becomes a series of beads lined up along the weld path.

Researchers in the United States, the former USSR, and Japan have devoted a significant amount of attention to this problem, but its complexity has always eluded the formulation of a generally accepted theory.

A technique developed at the Massachusetts Institute of Technology in Cambridge was instrumental in developing an understanding of the problem by describing the behavior of the molten metal under the intense heat of the welding arc. Using the technique, called Order of Magnitude Scaling, we were able to identify the critical factors that limited welding speed and provide guidance on ways to increase speed without introducing defects. Laboratory tests at MIT showed 20 percent speed increases in successful welds of stainless steel.

A method developed at MIT was applied to the complex forces that determine welding speed.

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Order of Magnitude Scaling also has been applied to problems outside welding. Research into plasma arcs at MIT has corroborated the few accepted scaling laws known for the arc and provided several new, previously unknown laws. OMS has been applied to ceramic-metal bonding and clarified the essential features of a strong bond between brittle and ductile materials.

But exactly what is Order of Magnitude Scaling?

Veteran engineers are known for steering directly to the core of a problem to reach an approximate answer. Regardless of their field of expertise, all of them follow essentially the same thinking patterns. On the other hand, less-experienced engineers often get caught up in details that make their reasoning more difficult and, in some cases, stall in front of an apparently intractable problem. Order of Magnitude Scaling attempts to reproduce in a computer the thinking mechanism of veteran engineers.

Thinking Processes

What are these thinking patterns that enable veteran engineers to see through complex problems? Although their reasoning is fluid and intuitive, the following four steps summarize the essence of their thinking process:

First, veteran engineers divide a system into subsystems. Sometimes the division is invisible to the eye. For example, in a plasma arc there is an "inside region" and an "outside region," but there is no material wall that divides them.

Second, veteran engineers perform a balance for each subsystem. Typical balances are conservation of mass, conservation of energy, or equilibrium of forces.

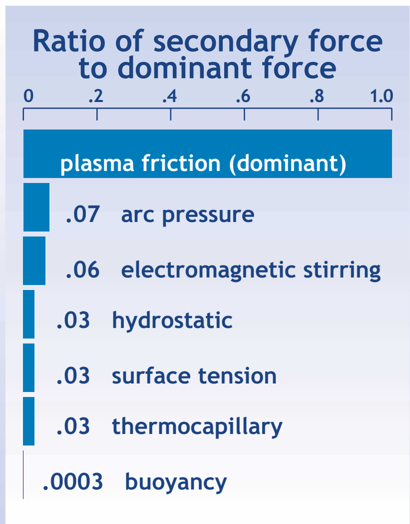
Third, for each balance, veteran engineers consider the extreme cases where one factor dominates all others. Their intuition, based on experience, guides them through the selection of the dominant effects. OMS provides a systematic complement to these traditional techniques that rely heavily on intuition by attacking the problem with a rigorous algorithm, checking all possible factors to identify those that dominate.

Fourth, after they solve the simplified balance, veteran engineers verify that the elements neglected in the balance are indeed small. If this is not the case, a new choice of dominant effects must be made. These iterations are very time-consuming, and can be performed by hand or intuitively for only relatively simple problems. Order of Magnitude Scaling hands over this task to a computer, expanding decision-making far beyond the range where only the experts can operate.

The mathematical basis of OMS integrates well-established tools to turn the four steps into a computer algorithm. Two very well-known mathematical techniques incorporated into OMS are Dimensional Analysis and Simplification of Equations.

The former is a traditional engineering technique first used by Joseph Fourier in the development of his theory of heat transfer in the early 19th century, and formally stated by Edgar Buckingham in 1914 in the form of the Pi theorem. The second discipline, Inspection of Equations, consists of generating dimensionless groups, and making educated guesses based on the expected relevance of different terms in the governing equations of a system.

Variations of these techniques are ubiquitous in engineering and applied mathematics. OMS synthesizes engineering fundamentals such as analysis of differential equations, applied concepts like matrix algebra, and other recent disciplines such as artificial intelligence.



The authors concluded that plasma friction by far dominates among forces affecting high speed welds.

Order of Magnitude Scaling is related to a broad spectrum of engineering techniques. It provides simple and accurate formulas in the early stages of design, when the configuration of a machine or system must be determined. This is especially useful when new processes are involved and there is no precedent set by similar machines from which to get design guidelines.

How It Differs From Other Techniques

OMS differs significantly from techniques such as finite element analysis and computational fluid dynamics in that OMS provides formulas instead of numerical results. For instance, CFD of the plasma arc provides the velocity distribution of the plasma for every point of the arc, but if we need to know how the maximum plasma velocity varies with current, several computer runs are necessary, one for each data point. Still, this information is constrained to the particular gas and arc configuration chosen.

In contrast, OMS provides a formula that clearly shows this trend and its dependence on other parameters. The formula gives the designer a tool to build with. While CFD and FEA give answers for particular cases, OMS gives an approximate answer to a whole family of problems simultaneously.

OMS differs from experiments as well by providing formulas rather than measurements. Also, OMS doesn't involve the integration of the differential equations or any other computational discretization. While Dimensional Analysis and Inspection of Equations also provide formulas instead of just numerical values, OMS can deal with much more complex problems than those using manual analytical techniques.

The essence of OMS can be illustrated by looking at the limitations in high-productivity welding. The goal is to increase productivity through faster welding. The key to increasing speed is to understand what happens to the molten metal under the arc. The governing equations for this problem are multicoupled, which means that they are interdependent at many different levels.

The forces that cause motion and heating in the metal are closely interrelated, and can be described with eight equations involving 18 physical parameters. The equations consider coupled heat transfer and fluid flow driven by plasma velocity, electromagnetic forces, gravity, and surface tension forces. The physical complexity of the problem is much greater than that of a standard fluid flow problem. While a standard fluid flow problem can be complex and computationally taxing, the essence of the physics is still much simpler than that of a coupled problem.

Typically, veteran engineers can identify the physical phenomena acting on a problem. In a very deformed weld pool, phenomena such as fluid flow, capillary forces, or electromagnetic forces can be readily identified. When these forces don't interact with each other, experts can quickly arrive at useful approximations. When these forces are coupled but involve only two or three forces at a time, causes and effects cannot be discriminated easily.

Physical insight and experience help the best experts to extract general rules about the behavior of the system. These experts arrive at the general rules by trying different combinations of hypotheses about what is important and what is not in the problem.

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When the problem involves several equations and parameters, and the coupling involves more than two or three forces interacting with each other, the number of combinations reaches beyond human capabilities.

Typically, there are few generally agreed approximations or none for this type of problem. The weld pool is one of these types of problems.

In laboratory tests using low-sulfur steels, the rate at which successful welds could be completed was increased by 20 percent.

Historically, engineers attempted different educated guesses for the root cause of the defects limiting welding productivity because they lacked a basic mechanistic explanation. Most of this work arose from extrapolating experimental and numerical data for slower welds. Electromagnetic stirring, thermocapillary forces, plasma pressure, and plasma friction were all suggested as root causes by different scientists.

All these forces are always present during the welding process, but they are not equally strong. In fact, many of them are so small that they can be neglected. The challenge is that we need to eliminate these negligible forces to make the problem tractable, but we don't know which forces are negligible until calculations have been performed. Using traditional numerical techniques we are deadlocked.

The Dominance of Plasma Friction

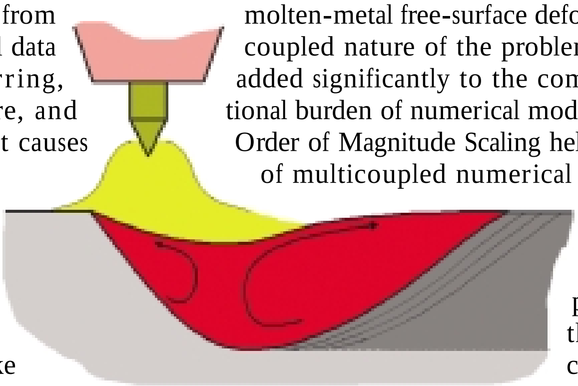
Through iterations of available calculations and order of magnitude approximations, OMS identified plasma friction as the dominant factor governing weld pool distortion. Later, in laboratory tests, it was observed that plasma from the arc causes a strong wind toward the back of the weld where it spreads the molten metal into a thin layer. This thin liquid layer is very unstable and can solidify unexpectedly, causing serious welding defects. With this knowledge, several strategies to improve welding productivity were evident. For instance, at MIT we could increase the maximum welding speed on stainless steel by 20 percent by selecting steels with low sulfur content. Capillary forces in molten low-sulfur steels contribute to greater resistance to the plasma wind.

If we consider the contribution of the different forces acting on the weld pool when compared to the dominant force, plasma friction, we realize that buoyancy is less than a thousandth of its magnitude, negligible by most standards. On the other hand, the forces induced by the arc pressure are 7 percent of the magnitude of the forces induced by plasma friction. The arc pressure can be neglected or not, depending on the desired accuracy in the calculations.

Using Order of Magnitude Scaling, the ratio of each force to the plasma friction can be summarized graphically, synthesizing in just one graph the complexity of all the physics involved in the problem. Such a graph is the result of considering the effect of all forces in the molten metal, but using only the dominant factors to find scaling laws. This way, the governing equations for fluid flow are turned into a balance between aerodynamic friction of the arc over the welding surface, and the viscous forces of the molten metal in motion.

Overcoming Limits

Numerical models were frequently limited in dealing with welding at high velocities, because of the very large molten-metal free-surface deformation and the multicoupled nature of the problem. Coupling of factors added significantly to the complexity and computational burden of numerical models.



A schematic shows the flow directions of molten metal (red) under the welding arc.

Order of Magnitude Scaling helped avoid the problems of multicoupled numerical solutions, because the modeling aspects causing numerical complexities had very little physical relevance and, therefore, could be discarded. This greatly simplified the problem.

In numerical models such as finite element models, we don't know what is negligible until the whole problem is solved. If we cannot solve it, we cannot know what could have been discarded. OMS, on the other hand, can determine the dominant factors even in very intricately coupled problems. These results can then be used to make the numerical model tractable.

Another significant difference between numerical approaches and OMS is that numerical models provide results only for specific cases, valid only for the value of the parameters used. If any parameter is changed, however slightly, all the calculation must be run again. OMS provides results in the form of formulas, which can be used

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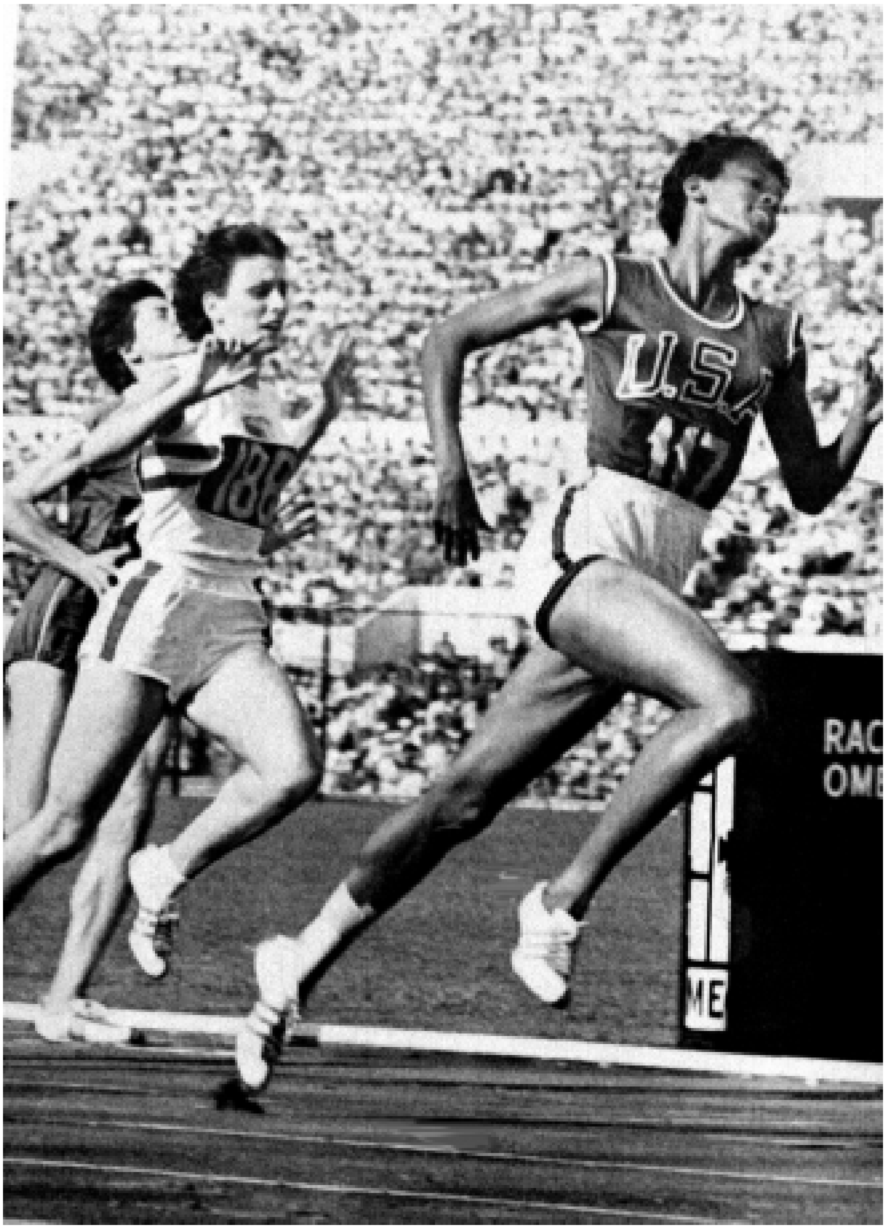

Thermal management of athletes is a complex problem in which many forces vie to heat or cool the player. Defining a balance of heating and cooling flows helps to classify different needs and conditions.

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for different combinations of parameters without the need to run the OMS algorithm again.

The thermal management of athletes is a very different problem from welding that carries similar challenges. The objective for athletes is to maximize performance by intelligent management of an athlete's heat balance.

This can be accomplished in many ways. One way is to reduce perspiration, thus making more blood available to the muscles. Another way is to exploit a transient heat balance to improve athletes' performance for limited duration. Some athletes even "pre-cool" their bodies by using ice vests before a competition to compensate for generated heat.

The optimization of thermal balance can drive the selection of clothing and type of fabric to be used during training and competition. While for extreme cases of temperature, humidity, and relative airspeed, the choice of clothing might be obvious, greater challenges are posed in choosing the optimal clothing for intermediate conditions. Below what temperature do athletes perform better with long sleeves? How does this depend on humidity? Is this affected by airspeed or athletic discipline? At the highest competitive levels, the answers can be the difference between gold and silver.

The problem is complex, because there are many simultaneously acting physical processes competing to heat or cool the athlete. By using Order of Magnitude Scaling to balance the heating and cooling flows, it is possible to classify different sports and ambient conditions into different categories with clear boundaries.

This division into categories is invaluable in making complex decisions quickly, based on information available from the weather report, athletic discipline, and athlete's condition. The division in categories with clear boundaries constitutes a "process map" for heat balance. In this case, the process map indicates the dominant heating and cooling processes for different temperature and humidity conditions.

OMS has been used to analyze welding, clothing for athletes, plasma arcs, ceramic-to-metal bonding, wire heating systems, and several other basic problems that could be calculated or measured, but that lacked scaling laws. The current effort on OMS itself focuses on developing a user interface that will allow faster application of the method, an important requirement for widespread industrial use.

OMS and other scaling methods bring the equivalent of experience back into an engineer's toolbox. These methods are exciting, as they bridge the gap between simple problems that can be solved analytically, and complex numerical problems that can be solved only after significant effort and yet only provide limited opportunities for generalization.

The technique is robust and rigorous. Although some time is involved in formulating the problem, the payback is direct identification of dominant factors and formulas to assist in the engineering of processes and designs. We believe that this new tool, Order of Magnitude Scaling, will find increasing use in a variety of new applications over the next decade. ■