THE JOY OF WELDING

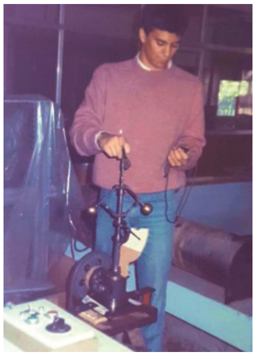
I was first exposed to welding as a little kid when my dad taught me the basics while building a camper trailer. I was able to use this knowledge again during my wind-energy research in Argentina. This particular project was so severely underfunded that I had to use discarded stubs from the shop floor. I continued my interest in welding during my doctoral studies at MIT. Although my interests were mostly theoretical, I felt that welding was a breathtaking channel and I was keen on developing my skills to the fullest. Thus, started my love affair with welding, and a life of fulfillment, excitement, and friendship. During my unique path into welding, I learned many things that are often overlooked, which I wish to share now. My story is not an exhaustive account of my journey, but a peek into the thrilling world of welding.

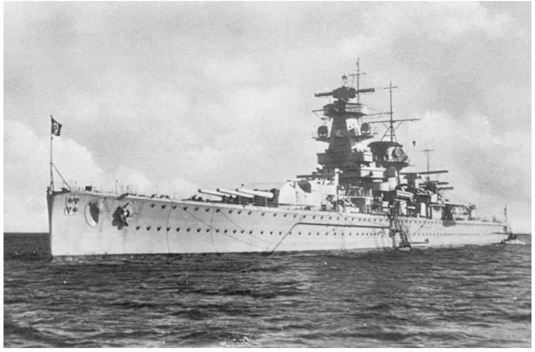
WELDING IS EVERYWHERE

There will be a weld in almost all things made of metal, whether it's a bridge, a rocket ship, or a cell phone. **Life and death** can often be separated by the ***knowledge of welding.***

In 1980, the $200 M Alexander Kielland offshore oil platform collapsed and sunk in the North Sea with the loss of 123 lives. The cause was an unplanned maintenance weld on a non-structural member that could have been avoided with a proper understanding of welds.

After losing WWI, Germany was forbidden from building war ships heavier than 10,000 tons; significantly smaller than the prevailing 45,000 tons of state-of-the-art battleships at the time. In the buildup to WWII, before breaking the limits, engineers used welding to create "pocket-battleships, " that were as powerful as their traditional counterparts. Welding (enabled by the development of low-hydrogen electrodes), enabled the replacement of rivets, eliminating the excess weight of lap joints. The most famous of these pocket battleships, the Graf Spee, raided the oceans sinking nine allied ships. The Royal Navy needed to dispatch nine forces across the seas to find it and eliminate its threat. After severely damaging the pursuing fleet, the Graf Spee was cornered at the






mouth of the River Plate, and was scuttled by its crew in front of Montevideo (Uruguay), where it rests to this day. A knowledge of welding resulted in the seafaring power for the Germans.

Welding was also a significant contributor in the defense of the Soviet Union during the German invasion in WWII. The Soviets developed the T34 tank to oppose the German Panzer and Tiger tanks. The T-34 had many mechanical and quality problems, and the statistics for 1941 show a loss ratio of approximately 7-1 between Soviet and German tanks. At the battle of Kursk, the largest tank battle ever fought, the ratio approached 8-1. Yet, the Soviets defeated the Germans. For all of its shortcomings, the T34 had an advantage that the Germans did not. This advantage was the use of submerged arc welding (SAW), which enabled an increase in productivity by a factor of 8 to 10 over manual welding, as was used for German tanks. The leader of this welding achievement was **Dr. Evgeny Paton**, who became a celebrity in the Soviet Union, and was awarded their highest civilian honour (Hero of Socialist Labor), named Vice-President of the Ukranian Academy of Sciences, and went on to develop the **Paton Welding Institute,** one of the largest welding institutions in the world. Today, a T-34 tank stands at the doors of the Paton Welding Institute reminding everyone of the pivotal role of welding in saving the nation.

The goal of the Apollo mission: “Before this decade is out, [] landing a man on the moon and returning him safely to the earth” was severely threatened by problems in welding the second stage of the Saturn rocket. Rocket bodies are made of welded aluminum, and aluminum welding is prone to porosity unless special care is taken. The problem was solved with considerable amounts of work and ingenuity in a near surgically clean operation.

The central tank of the former space shuttle (the big orange one) employed an advanced aluminum -lithium alloy that enabled weight savings to increase payload. The challenge with this alloy was that it was near-impossible to weld in practice. A new process (variable polarity plasma arc welding, VPPAW) was developed in Canada for the first flights and eventually replaced by the solid-state process of friction stir welding (FSW).
The main module of the Chinese space station was also welded using VPPA, which earned its developer **Prof. Shujun Chen**, the National Science and Technology Progress Award; one of the highest scientific awards from China.
The body of most rockets today (including SpaceX and Blue Origin) is welded with FSW. Welding is so central to rocket-building that there was a lot of pent up negativity between Elon Musk and Jeff Bezos when the FSW expert of SpaceX switched to Blue Origin.

Until recently, the fuselage and wings of all passenger airplanes were riveted. This all changed with the Airbus 380 (a double-decker aircraft capable of carrying up to 868 passengers) which introduced laser beam welding (LBW) of structural components in the wings and fuselage. Much like with the pocket-battleships of WWII, eliminating riveting resulted in abundant weight savings, enabling the enormous size of the A380. It took a massive effort of engineering and testing to make sure that the welded joints met and exceeded the requirements of strength, toughness, fatigue, and corrosion. The development of LBW for the A380 was considerably helped by the scientists that emigrated from the Paton Welding Institute after the collapse of the Soviet Union.

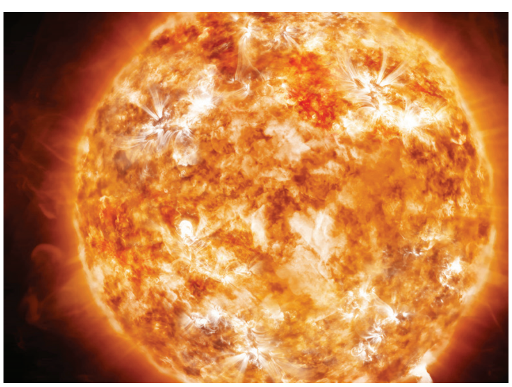
Another welded passenger plane is the Eclipse, in which FSW is used to save weight and automate production. Eliminating rivets helped speed-up the manufacturing of the aircraft, and FSW enabled

Left - right: 1. Patricio F. Mendez performing experiments on a centrifugal governor as part of research in wind energy. The frame supporting the governor was (very precariously) welded by him. 2. The price of not knowing welding, the collapse of the Alexander Kielland offshore oil platform. 3. Bundesarchiv, DVM 10 Bild-23-63-06 / CC-BY-SA 3.0, Panzerschiff "Admiral Graf Spee". 4. The Apollo mission almost missed its time-window because of welding problems. 5. The T34 Tank saved the Motherland.

the application of automotive-style series manufacturing, with enormous cost savings. Prototypes were first flown in 2002.

Military jet fighter planes are in a class by themselves with extreme demands of weight reduction, performance, reliability, and resilience. Electron beam welding (EBW) is employed in their construction and this is consistent with the use of titanium, which is highly reactive to atmospheric contamination, so it is best welded in a vacuum. Titanium has a strength comparable to that of steel with half the density, and its elevated price (approximately 10 to 20 times that of steel on a weight basis) is justified in the performance-dominated military applications.

In addition to the airframe, the landing gear and turbine engine shafts are also welded using friction welding (FW), which gives outstanding mechanical properties and enables the welding of dissimilar metals such as those best suited for either the hot and cold stages in the turbine. Diffusion welding (DFW) is used to weld the titanium fan blades of Rolls-Royce turbines.



Top - bottom: 1. This plane is so large because it is welded. The welding arc is faster. 2. This plane is so lethal because it is welded 3. Cast sculptures are actually welded sculptures. 4. This is the surface of the Sun. The welding arc is even hotter.

Welding is one of the main reasons that car bodies are made of steel and not aluminum. This is paradoxical because even bicycles have moved past steel but cars haven't One of the reasons for this is that steel can be welded using resistance spot welding (RSW), which is extremely economical and fast (each vehicle typically has 5000 spot welds), but this process is not well-suited for aluminum. Aluminum cars are still possible, but they are built with a technology different than steel cars. Steel cars typically have a "unibody" construction technique, where most body panels have a strength function. Aluminum cars such as Tesla Models S and X and the Audi A8 are built with a space-frame technique, in which beams carry the loads joined at nodes, and the body panels are attached to the space-frame but have relatively little structural responsibility. Aluminum cars rely considerably on adhesives and rivets; they are still waiting for their Graf-Spee moment. Welding is so crucial to car-making, that when new advanced high-strength steels (AHSS) were adopted, the adoption was slowed by the need to adapt the welding techniques to these new materials. Similarly, one of the main culprits in the delay in reaching full-capacity in the production of Tesla's Model 3 is the steep learning curve for mastering RSW at the massive production scales intended.

Heavy machinery such as the ones used in roadwork, farming, and mining depend on welding. Welding also enables modern steel structures and their innovative architecture. The cost and velocity of construction of pipelines is typically limited by welding. Even cast bronze sculptures are welded; the model created by an artist is turned into small parts which are cast, and then put together by welding, typically gas tungsten arc welding (GTAW).

The footprint of welding in the economy is enormous. Total welding-related annual expenditures in the US are of the order of $34 billion and involve 500,000 people in the workforce. These enormous expenditures are larger than the GDP of two-thirds of the world's nations. In Canada, welding expenditures are more than $5 billion, involving 300,000 people, 75,000 of the technicians or welders.

FANTASTIC VOYAGE INTO A WELD

We are all familiar with the sight of a welder, protected by a mask from flying sparks and a very intense bluish light. As we approach the welder, more detail becomes visible. The welder is holding an electrode connected to cables, and if we also put on a welding mask and look closely, there is molten metal under the electrode. This is just one of many possible welding processes, called shielded metal arc welding (SMAW or "stick" welding in common jargon). One detail, in particular, is especially interesting: the electrode is not touching the weld, but electricity is still flowing. How can that be? If electricity could flow through air, wouldn't we get shocked just by walking past an electrical outlet?

Question becomes, how is this possible?

HOTTER THAN THE SUN

Charged particles carry electricity; and in the case of welding, typically the electrons. During welding, some of the electrons (those in the outermost atomic orbits) become loose, thus conducting electricity in a manner not too different than electricity is conducted in metals. Incredibly, the gas is behaving like a metallic conductor.

This behavior is not normal; it is only possible because the gas between the electrode and the weld is incredibly hot, of the order of 20,000 K in GTAW and 10,000 K in GMAW (K means Kelvin, the unit of absolute temperature). For comparison, the surface of the Sun is at 5,800 K. Welders might not know it, but during welding, they are holding something much hotter than the Sun in their hands.

At the extremely high temperatures of the gas during welding, the vibrations of the gas molecules are powerful. Similar to vigorously shaking an apple tree and having the fruit fall, some electrons that are typically attached to the atoms also become loose, making the gas conductive. A gas in this condition is called a plasma, which is the fourth state of matter, beyond solid, liquid, and gas. The plasma between the electrode and the weld is called an arc; which is a word at the root of the name of so many welding processes.

This conductive gas still has electrical resistance, and the current flowing through this resistance is the source of the heat that raises the plasma to such high temperatures. The amount of heat created at the arc is of the order of kilowatts (comparable to the energy consumed by a clothes iron), but it is concentrated in a much smaller volume (of the order of 300 times smaller) resulting in an incredibly intense heat source. Fusion welding of steel, in which the steel is molten during welding, started simultaneously with the discovery of the electric arc. Before this discovery, the available sources of heat (typically flames), were not intense enough to melt steel.

Paradoxically, an arc is self-sustaining. The hot gas in plasma state conducts electricity, generating heat, thus maintaining its plasma state indefinitely. Conversely, a gas at room temperature does not conduct electricity, does not create heat, and will maintain its insulating status indefinitely. This is the reason why we can walk by an electrical outlet without being zapped, and also the reason why arc start is so important to welders, and arc stability such a prized attribute of welding machines. Most of the heat of the arc is lost in the form of light in the blue and ultraviolet wavelengths. Such intense ultraviolet exposure can cause skin cancer or severely injure eyesight; this is the reason behind the mask, jacket, gloves and other protection used by welders, and also the reason why viewers can only watch a welder closely if they use similar protection.

FASTER THAN A PLANE

It is well known that electricity creates magnetic fields and that the interaction of these electric and magnetic fields results in forces; this is the functioning principle of electric motors, such as those in modern electric cars. An especially interesting aspect of welding arises when we realize that these electromagnetic forces are applied to the plasma, which is a fluid that cannot resist these forces and thus start to flow. The field of science needed to study the welding arc is called "magnetohydrodynamics," and was pioneered by **Hannes Alfven** during his studies of the surface of the Sun and interstellar space, for which he received the Nobel Prize in Physics in 1970.

The intensity of these "magnetohydrodynamic" flows during welding is surprisingly high; for the case of GTAW, they are of the order of 300 m/s. To put it into context, the cruise velocity of a passenger plane is of the order of 250 m/s. *In addition to holding something hotter than the Sun, a welder is handling something faster than a jet plane.*

The swift flows in the arc can cause problems during welding. Their intensity increases with current, and beyond certain levels, and the force created by the velocity of the plasma can blow the molten metal away from the weld resulting in an unacceptable defect called "humping," which is present when welding at high currents. This is the reason why there is a limit to productivity increases obtained by welding with faster travel speed and higher welding power. I did my Ph.D. in humping, which never fails to amuse audiences.

LISTENING TO A WELD'S HEARTBEAT

Welds have a "heartbeat." In arc welding, the current and voltage vary within fractions of a millisecond, and these variations have a signature, such that it is possible to assess the "health" of a welding process by looking at their "EKG," which are the measurements of current and voltage over time.

For the case of GMAW (often also called "MIG"), the electrode is a wire that melts, adding material to the weld. The wire might melt regularly or irregularly, in the form of a few big droplets or many small droplets, and the electrode might or might not touch the weld, each case showing clear characteristics in its current and voltage graphs. The way the droplet detaches from the wire is fundamental to the welder and the weld. When the wire melts in the form of fast, small droplets (typically called spray transfer), we can have accurate process control and high-quality welds, but this requires expensive gases such as Argon, and high welding currents, which can be excessive for welding thin components. When the wire melts in the form of slow, big droplets (typically called globular transfer), we can use cheaper gases such as CO^2, but the droplets do not always fall in the right place in the weld and can cause spatter (splashing) in the molten metal when the droplets "cannonball" into the molten bead. When the wire electrode touches the weld (typically called short-circuit transfer), an electrical short-circuit is created, which can result in molten metal droplets (spatter) flying in all directions. Because the average voltage and current can be low in short-circuit transfer, thin components can \be welded without burning through them. All these characteristics can be analyzed in detail through the weld "EKG," often used together with a high-speed video which enables welding engineers to see what the human eye cannot. The startling innovation in welding power supplies in the last decade is due in large part to this understanding. Even today, there are aspects of current and voltage graphs that cannot be explained and are the focus of intense research.

NOTHING ESCAPES WELDING

Music is a good analogy for welding. Let our imagination fly to a concert hall in Italy in the early 1800s. **Niccolo Paganini** is playing Mozart's work. Paganini is a well-known virtuoso, and he is the most celebrated violin player of all times. He is suspected of having made a pact with the devil to reach his level of talent. He is playing his Stradivarius violin, made by Antonio Stradivari the maker of violins considered best, even now after 200 years. Mozart is the best composer of his time, with easily recognizable pieces The technique and manual dexterity of Paganini are unequal, his ear unerring, the sound of his violin is exquisite, and the piece he's playing is sublime.

Back in our welding world, Paganini is a welder, also with excellent manual dexterity and a finely tuned ear, able to do what few other people can, resulting in a product of much beauty and pride. Besides, the welds have a function beyond their beauty. Stradivari is a welding engineer, maker of welding machines, and the exquisite sound of the weld is the result of years of research to accomplish the perfect arc stability, metal transfer, and response to the welder's commands. Mozart is another welding engineer, whose composition is called a welding procedure, and whose musical notes are the welding parameters such as current, voltage, electrodes to use, and many more details.

To get to our concert, we also needed to buy the tickets; and to learn, Paganini needed a teacher (who he quickly surpassed); and for the theater to run, a manager is necessary. Even music critics were present. Similarly, welding is only possible through distributors and salespeople, welding instructors, managers, business people, welding inspectors and the list continues.

We quickly realize welding is much more than the act of putting down metal. A whole community is needed. Welding is a chain made of unique links, and any broken link breaks the entire chain.

Even if we look at the technological aspects of welding, we see that it involves an extensive range of disciplines. Metallurgy is needed to understand the behavior of the metal as it heats and cools and its resulting properties such as strength, hardness and fatigue life. Chemistry is required in order to understand the chemical reactions that happen in the molten metal, where chemically reactive elements are introduced on purpose and are the source of many patents and trade secrets. Chemistry is also needed to understand corrosion behavior. Mechanical engineering is necessary to explain the forces and distortions at play during welding, as well as to design and implement automation and robots. Electrical engineering is needed to understand and develop the electric power sources and their controls, as well as the control equipment of welding automation. Civil engineering is required to understand the system-level performance of welds and to design the welds present in bridges and buildings. All these disciplines are based on physics, which studies the behavior of heat, the motion of fluids, and the properties of plasmas. The language of physics is mathematics, which is tricky in welding, given the large variety of phenomena present ("Multiphysics"), and how tightly interdependent they are ("multi-coupled"). Beyond the complexity present during welding; non-destructive testing is necessary to ensure quality. Welding is only feasible when the economics are favorable and also experts in logistics and risk assessment are part of the community that makes welding possible.

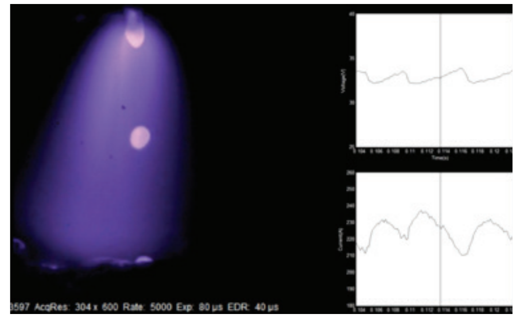
I WANT TO WELD!

The reach of welding is so vast that it can be seen as an avenue to fulfill any calling we have in life. Welding can be an excuse to do whatever we would like to do. Our call can be to make welds and be the Paganini of welding; it can be to become an engineer and be a Stradivari or Mozart of welding, or to become a businessman and make more money than all of the above combined. The paths are not exclusive. Paganini was not only a virtuoso but also a composer; similarly, in the right conditions, welders can also develop welding procedures or invent equipment.

Eminent people have been involved with welding. The Wright brothers made their welding machine in their shop in Ohio. Svetlana Savitskaya performed the first spacewalk by a woman to test electron beam welding (EBW) in space. Comfort Adams was a professor of Electrical Engineering at Harvard when he founded the American Welding Society. Welders can accomplish incredible feats, from welding at the depths of the ocean to incredible heights (the sky was not the limit for Ms. Savitskaya), from welding in the extreme cold to extreme heat. Similar to rock-stars, the best welders can work with weld on their backs. Welding trucks are better suited than a Batmobile, and emergency calls involve as much adrenaline as emergency medicine.

Whether it is in an office or open air, thinking or doing, working with ideas or with our hands, welding has provided an avenue for fulfillment to many and has been central to the development and survival of nations. ***The world comes together because of welding.*** W

▶ **Patricio F. Mendez,** Director of Canadian Centre for Welding and Joining at University of Alberta



Top - bottom: 1. Current and voltage signals show the heartbeat of welding. 2. The first spacewalk by a woman was to weld in space. 3. Dad *talks* about welding, but I *know* welding.