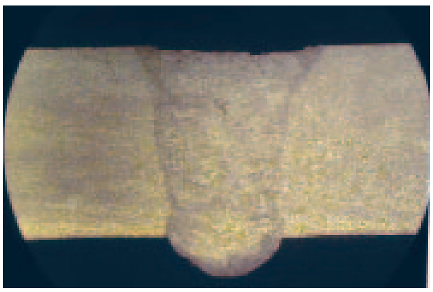
# Plasma Window Developed for High-Quality Electron Beam Welding in Atmosphere



*A complete penetration weld in 0.125-in.-thick 316 stainless steel at a travel speed of 15 in./min at 3 kW of power.*

For many years, manufacturers and engineers have strived to develop an electron beam welding (EBW) technology that could offer all of the advantages of the various types of EBW while minimizing their respective limitations (see boxed item). Acceleron, LLC, and Ady Hershcovitch from the Brookhaven National Laboratory are currently developing a mechanism referred to as the "plasma arc window" that may realize these advantages.

Acceleron, an electron beam and laser service company in East Granby, Conn., was awarded a $525,000 grant from the U.S. Department of Energy (DOE) to work with Brookhaven National Labs to develop and commercialize this new welding technology. The grant is administered by the Connecticut Department of Environmental Protection. Additional funding came from Connecticut Light and Power Co. (CL&P), which granted $250,000 because of the potential for energy savings and reduced pollutants. Acceleron will also contribute more than $500,000 to this program. It holds an exclusive license to the welding technology patented by Brookhaven.

The purpose of the plasma window is to produce high-quality electron beam welding and drilling in open air without the restriction of a vacuum chamber. The invention embodies a stabilized plasma arc, configured to function as a "window" that can confine the high vacuum required to form the electron beam, while allowing the electron beam to pass through it unimpeded. The energetic particles forming the plasma window are analogous to rushing water molecules in a powerful waterfall. A child's ball tossed against the waterfall will be easily deflected, just as plasma particles will easily deflect the low-energy molecules in air. Conversely, a bullet fired from a gun will readily pass through the waterfall, similar to the passage of the electron beam through the plasma window.

## Principle of Operation

The plasma itself is a collection of charged particles at high temperature, confined by electric and magnetic fields. The density is low enough to be essentially transparent to an electron beam but dense and hot enough to contain a high vacuum necessary for electron beam formation. Thus, the window functions as a transparent barrier between high- and low-pressure regions. Another feature enhancement is that the plasma window also functions as a very effective focusing lens by squeezing the beam into a small spot size just prior to entering atmosphere unlike what can be done with traditional nonvacuum EB machines resulting in deeper, more narrow welds with less energy input.

Three effects allow certain plasmas to provide effective separation between vacuum and atmosphere and separation between vacuum regions, and to act as a pump. They are as follows:

**Gas pressure effect.** For a particular volume V, the pressure P is described by the equation PV=nRT, where n is the number of gas molecules, T is the temperature, and R is the universal gas constant. In the plasma window, T=15,000 K compared to room temperature of 300 K. Therefore, the plasma window matches atmospheric pressure with only one-fiftieth the density of normal atmosphere.

**Viscosity effect.** Viscosity (friction, resistance to flow) of a gas increases with temperature. Consequently, the gas flow through a hot plasma-filled channel is substantially reduced compared to that of a room-temperature gas-filled channel.

**Pumping effect.** Gas atoms and molecules are ionized by plasma electrons and are trapped by the fields confining the plasma window.

These effects can lead to a pressure reduction improvement over differential pumping by a factor of 22,000.

The plasma window also functions as a strong concentrating lens for charged particles like electrons. This realization provides an additional benefit of focusing the electron beam into a small, uniform spot size. A small spot size is a major factor in developing the high energy densities that provide some of the advantages of the electron beam processes.

## Energy Savings

Electrical savings of approximately 80% are projected by eliminating the roughing and diffusion vacuum pumping required for vacuum chamber evacuation. Efficient vacuum differential pumping equates to less energy consumption, resulting in large cost savings such as those achieved with conventional nonvacuum EBW. One of the project's major goals is to achieve a satisfactory separation and preservation of the high vacuum area where the electron beam itself is generated, while enabling its transmission to atmosphere. Results thus far have confirmed the attainment of excellent electron beam transmission. The accomplishment of this endeavor in itself has shown results that have significantly more advanced vacuum separation than conventional nonvacuum EBW. The improved vacuum stages that are necessary for vacuum separation are attributed to one of the functions the plasma arc window offers. Most of today's nonvacuum machines typically require a total pumping capacity of approximately 3200 $ft^3$/min to attain necessary separation. The plasma arc window provides far better energy consumption results with only 42 $ft^3$/min, or 91.5% less energy consumption.

Additionally, EBW and pulsed EB machining could effectively regain market share from YAG and $CO_2$ laser processing due to their better welding quality, energy efficiencies, and no-longer-required vacuum chambers. The electron beam processes are inherently 65–75% more total energy efficient than laser welding and cutting exclusive of the enhancement of the plasma arc window.

Following are the advantages and cost savings over conventional nonvacuum electron beam welding machines:

- Current overall total is 70% more energy efficient
- Having much smaller vacuum pumps reduces floor space by 90%
- Significant noise reduction due to the elimination of large vacuum pumps.

## Advantages EBW

Electron beam welding (EBW) offers users the following advantages:

- Low heat input at the weld zone, minimizing thermal distortion and stress
- High depth-to-width ratios
- Small heat-affected zone due to lower heat input required to achieve weld depths
- High-purity welds with no contamination from surrounding atmosphere such as oxides and nitrides
- High welding speeds
- Precise, repeatable welds
- Ability to weld similar and dissimilar metals
- Welding in high-, partial-, or nonvacuum environments
- Minimal to negligible weld shrinkage

### Comparisons and Limitations of the Three Different Weld Methods Available

High-vacuum electron beam welding (EBW-HV) has a significant limitation that restricts its usefulness in high-production applications: welding must be accomplished in an evacuated chamber, which is pumped down typically to the $10^{-4}$ torr range. The chamber restricts the size and the number of the workpieces that can be welded, and the vacuum pumping cycle consumes time and energy.

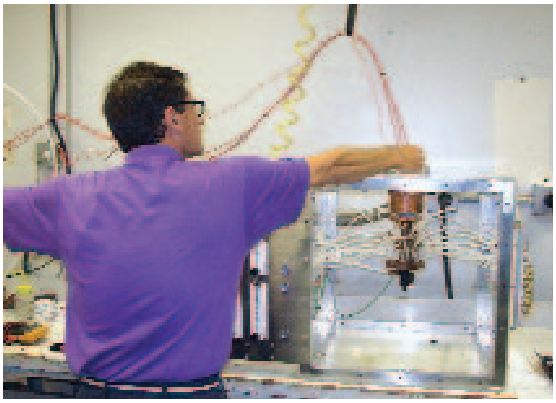
Some EBW machines operate and weld at a partial-vacuum chamber pressure range of $3 \times 10^{-3}$ to $3 \times 10^{-1}$ torr and are referred to as EBW-MV. This process increases part throughput due to the decreased vacuum evacuation time required prior to welding, but still consumes time and energy. Although the welds are performed in a partial vacuum, they are not as high in quality as with EBW-HV. Weld geometry and penetration at a given power are also affected. The penetration is typically 5–10% less than EBW-HV and the welds are wider and more tapered.

A traditional nonvacuum electron beam welding machine (EBW-NV) welds at atmospheric pressure and is used for high-production welding. Because there is no vacuum chamber, there is no pump-down time required, resulting in higher throughput than that of EBW-HV or EBW-MV with even lower production costs per piece part. Helium is used to reduce beam scattering, increase the beam "stand-off distance," and to minimize weld contamination. The weld depth-to-width ratio with this process is further decreased along with the distance where the beam exits. The purity of welds produced by this method is generally not as clean as with the other two EBW processes. The EBW-NV process still provides good-to-excellent welds, but not without decreased weld penetration and increased weld width.

## Project Goals

The major goals for the plasma arc window project are to

- be at least 80% more energy efficient than today's conventional EB and laser machines.
- replace energy-inefficient technologies with the same or better weld results.
- decrease welding costs.
- replicate a high-voltage, high-vacuum EB weld as best as possible.
- make this new technology mobile so that it can be used on a robot or other motion-type systems.
- weld, drill, and, in theory, cut and machine.
- decrease floor space and cost of current high- and non-vacuum EB machines.
- commercialize and sell this new technology as a retrofit to existing machines and incorporate into new equipment.
- find other applications outside the welding industry.



*Scientist Ady Hershcovitch making gas adjustments to the plasma arc window.*

On April 29, 2004, Acceleron demonstrated to the DOE nonvacuum EBW using an electron beam transmitted from machine vacuum to atmosphere through the plasma window. Attendees witnessed nonvacuum welding of three samples using a 6-kW EBW machine. The demonstration showed repeatable results were achieved. The next development step is to retrofit a high-power (25-kW) production EBW-NV machine to provide side by side weld comparisons utilizing the plasma arc window. The company expects to achieve deeper, narrower welds than conventional nonvacuum machines using the same power and feed rates. Once this has been completed and repeatable results demonstrated, the company will begin to weld with this new technology on a production basis. This is expected to occur sometime this year.◆