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# Non-vacuum electron beam welding through a plasma window <sup>☆</sup>

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## Abstract

The plasma window is a novel apparatus that utilizes a stabilized plasma arc as interface between vacuum and atmosphere or pressurized targets without solid material. Additionally, the plasma has a lensing effect on charged particles. This feature enables beam focusing to very small spot sizes and overcoming beam dispersion due to scattering by atmospheric atoms and molecules. Recently, the plasma window was mated to a conventional electron beam welder. And, electron beam welding in atmosphere was accomplished with electron beams of unprecedented low power and energy. Weld quality for the non-vacuum plasma window electron beam welding approached the quality of in-vacuum electron beam welding. Indications exist that electron beam attenuation is lower than theoretically predicted. Results suggest that air boring was achieved with 6–15 mA, 90–150 keV electron beams compared to the previously used kA, MeV electron beams. It may explain the better than expected welding results.

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## 1. Introduction

Electron beam welding (in-vacuum) has many well-known advantages over other welding techniques, among which are: very high depth-to-width ratio of the weldments, very high energy efficiency, low distortions and the ability to weld reasonably square butt joints without filler metal addition. Electron beams must be generate and

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accelerated in vacuum. It is possible to transmit these beams to atmosphere through differential pumping section or foils in a few cases. Due to electron beam degradation in differentially pumped sections (or foils), non-vacuum electron beam welding does not possess all these advantages. Consequently, the vast majority of electron beam welding is performed under vacuum. Some of the shortcomings of vacuum welding are low production rates and limit on the size of assemblies to be welded (set by welder vacuum system). To rectify the shortcomings of present day vacuum–atmosphere interface, differentially pumped chambers and orifices, or thin walls, are replaced by a short high pressure arc, which interfaces between the vacuum chamber and atmosphere and has the additional advantage of focusing charged particle beams.

Atmospheric arc plasma has been used to establish vacuum–atmosphere interface without any intrusive solid structures, forming a ‘plasma window’, which has been described elsewhere [1,2]. Gas target cells at 3.85 bar [3] and 9 atm [4] were effectively separated from vacuum with a plasma window. In other experiments, a 175 keV electron beam was transported from vacuum to atmosphere [1,2]. X-rays [5] and a 2 MeV proton beam [6] were successfully transmitted through a plasma window with negligible energy losses. In this paper in-vacuum electron beam welding through a plasma window is described.

## 2. Plasma window mating to the electron beam welder

Fig. 1 is a diagram of the new electron beam welder. A conventional in-vacuum S/N 645 PTR electron beam welder was modified. The welder consisted of an electron beam column that is mounted on top of a vacuum chamber that houses the components that need welding. Like many typical electron beam columns, the column contains an electron gun, an alignment magnet, a solenoid focusing magnet and a set of deflection coils that can steer and focus the electron beam into a target, which is usually located in the vacuum chamber. It is pumped by a 6 in. diffusion pump down to a

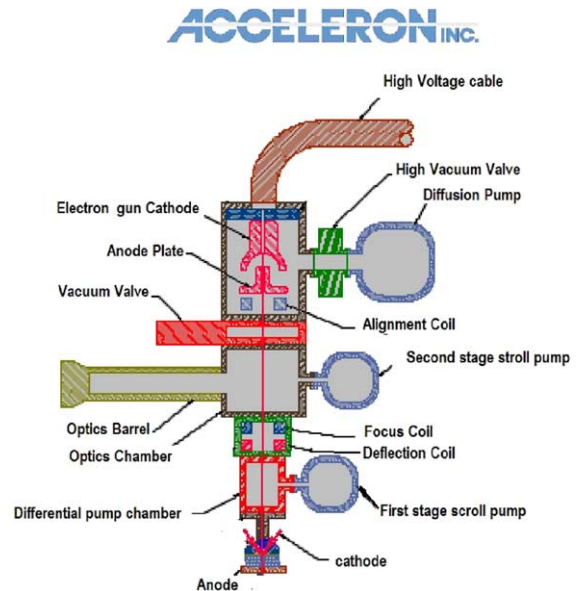


Fig. 1. Diagram of the electron beam welder to which a plasma window was mated.

pressure as low as  $5 \times 10^{-5}$  Torr; plans are to replace it by a turbomolecular pump.

In Fig. 1 configuration, a plasma window was mounted on a small ‘differential pumping’ chamber, which in turn was mounted on the bottom of the electron beam column to form the novel electron beam welder shown in Fig. 1. A 4 mm aperture, 5 cm long flow constrictor is mounted between that chamber and the optical chamber, both of which are pumped by 600 l/s scroll pumps.

Unlike all previous experiments that did not involve electron beams, the cathodes of this plasma window are on the vacuum side of the plasma window, since in this configuration the plasma window current focuses electrons. The plasma current generates an azimuthal magnetic field, which exerts a radial Lorentz force on charged particles moving parallel to the current channel. With present orientation of the current direction, the Lorentz force is radially inward. An unwanted consequence of this configuration is that the vacuum side of the plasma window must be kept at a pressure greater than 500 mTorr in argon and even higher in helium, i.e. an order of magnitude higher than plasma window vacuum separation

capability of as low as 32 mTorr [3,4]. Otherwise, the plasma window cathodes get overheated and lose their sharp points, which make it difficult to restart.

Since plasma window cathodes become white-hot, and since the plasma is very dense, the weldment can no longer be seen from the optical chamber. Additionally, the weldment needs to be shielded due to generation of X-rays during electron beam welding. Therefore, a TV camera is used to monitor the welding process.

As the electron beam passes through the plasma window, the window performance improves due to ionization and further heating of the arc plasma. Both the plasma arc voltage and the pressure in the first chamber drop when the electron beam is fired. For example, in an operation with argon helium mixture, pressure gauge reading (not true pressure) was 2000 mTorr with no electron beam. With an electron beam of 15 mA, pressure reading dropped to 750 mTorr; it dropped to 500 mTorr when the electron beam current was 20 mA; and, it was further reduced to 400 mTorr, with a 25 mA electron beam. Exact true pressure is unknown, since reading was done by a thermocouple gauge for which we have no calibration curves (it came with the welder), and since we do not know the ratio of helium to argon in that case.

Plasma window focusing effect is very pronounced. Fig. 2 shows the welder electron beam



Fig. 2. Welder electron beam propagating in atmosphere after exiting the plasma window.

propagating through atmosphere after exiting the plasma window. Its current and energy (from the gun) were 25 mA and 150 keV respectively. The beam is exiting on top from a 9/16 in. thick anode (from the plasma it propagates through atmospheric pressure helium argon gas mixture in the anode that cannot be seen in the photo). After that the beam is exiting the plasma window anode into atmosphere towards a welding table, which is 2 in. away from anode end. The bright spot on the table is due to the plasma window luminosity, which is dominated by its white-hot cathodes). Amazingly the electron beam 25 mA 150 keV seems to actually further ‘pinch’ during its first 1.5 cm in atmosphere. It is most likely evidence of air boring for the first 1.5 cm, i.e. pinched propagation in atmosphere. Previously it has been observed in multi-MeV, kA electron beams. But, it is a function of beam current density only [7].

### 3. Welding results

In atmosphere welds, performed with 150 keV electron beams, in stainless steel 316L 1/8 in. plates that exhibit full and partial penetration are shown in Fig. 3. Welds on the right were performed with the plasma window operating in argon–helium mixture with 42 mA extracted from the electron gun at welding speeds of 10.5 in. per minute (IPM) and 15 IPM for partial and full penetration, respectively. On the left side of Fig. 3 welds were performed with the plasma window operating in pure helium. Speeds for partial and full penetration were 20 IPM and 15 IPM respectively for electron beam gun current of 20 mA.

Heat zone (weld width) of all welds was independent of stand-off distances for up 3/4 in. However, the weld widths exhibit dependence on electron beam energy. For electron beams with energies of 150 keV, 140 keV and 90 keV, weld widths were 0.70 in., 0.050 in. and 0.035 in. respectively. In all cases, the current in the plasma window was 51 A, i.e. plasma generates azimuthal magnetic field was identical.

Other unique features of non-vacuum electron beam welding utilizing a plasma window are the achievement of this type of welding at the lowest

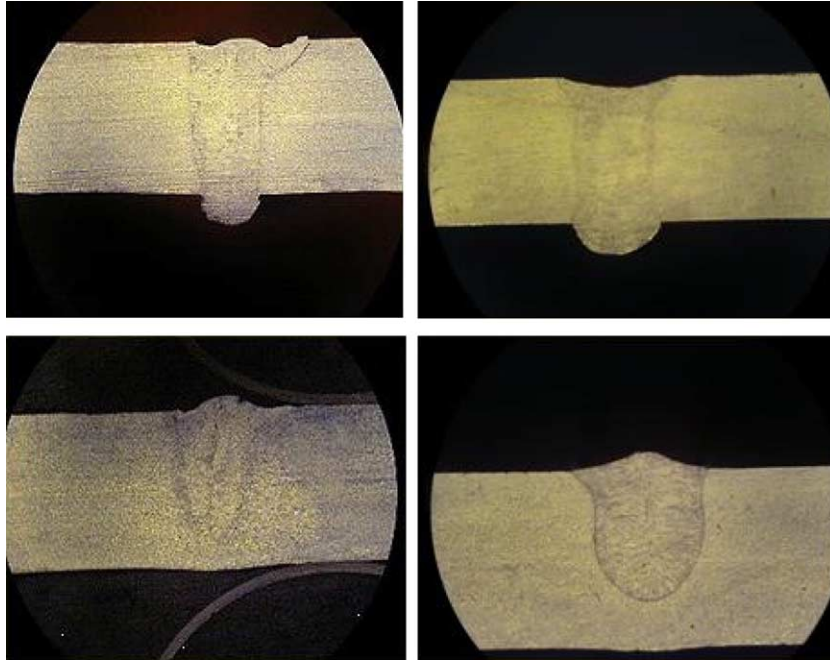


Fig. 3. Sample of welds made with an electron beam transmitted through the plasma window.

power and lowest electron beam energy ever. With the plasma window operating in pure helium, welding of 3/16 in. plates of 316L stainless steel was accomplished at an extracted electron beam power of 2 kW with a speed of 20 IPM. And, in-air electron beam welding was accomplished with 90 keV electron beams.

#### 4. Discussion

Weld quality evaluation and the bead shape consistency is at stand-off distances of a few millimeters to 50 mm, were judged by an independent expert [8] to represent a significant advance in out of vacuum electron beam welding technology. Elimination of the need for large vacuum systems for electron beam welding brings energy efficiency and floor-space savings [9]. The large difference in welding speed between operations in pure helium versus operation in helium–argon mixture, with the weld quality being similar remains a mystery. Speed depends on power deposition, i.e. should

be affected by beam attenuation, which depends on the gas  $Z$ , while weld quality depends on beam width (affected by scattering which depends on  $Z^2$ ). On possible explanation is that air-boring eliminates beam spreading.

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