Fig. 1 — Thin-film heated glass installed in an indoor SPA (courtesy of Thermique Technologies, LLC, www.thermiquetechnologies.com).

Simplicity and reliability are two advantages of low-pressure cold spray for producing bus bars in heated and photovoltaic glass

Cold Spray: A Solution for Architectural Glass

BY JULIO VILLAFUERTE

Glasses are amorphous materials with disordered atomic or molecular structures that result when any material (ceramic, metallic, or polymeric) is cooled from its molten state at a rate higher than what the material would require to transform into a more thermodynamically stable crystalline structure. The term "glass" is commonly associated with the glass derived from silica (SiO_2), limestone ($Ca.CO_3/Ca.Mg.CO_3$), and sodium carbonate (Na_2CO_3). For centuries, the unique properties of silica glass combined with the widespread availability of raw materials have made glass the choice material for an enormous number of applications. In modern glass works, flat glass (also referred as "float" glass) used in architectural or other applications, is produced by forming glass sheets over a bed of molten tin in large float tanks.

Over the last few decades, the window industry has witnessed innovative changes as a result of many improvements in window design, performance, and construction. In particular, the use of insulated glazing units has become widespread. They consist of a set of two or more lites of glass that are spaced apart and sealed into a single functional unit; the interpanel cavity is filled with gases, gels, or other substances to customize the heat transfer and optical properties of the unit.

Thin-film deposition techniques are also used to tailor the transmittance, reflectivity, and absortivity of architectural glass. More recently, thin-film deposition techniques are being utilized to transform architectural glass into highly functional

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devices such as heated glass and photovoltaic glass. An important characteristic of these futuristic glass units is their ability to electrically interconnect with the outside world. This article discusses the economical and technical benefits of low-pressure cold spray technology to provide such interconnectivity.

Heated Glass

When the temperature differentials between the inside and outside surfaces of a glass window are extreme (e.g., during cold winters, hot summers, and in refrigeration systems) one side of the panel might be cold enough to promote water condensation (fogging) or even solidification (icing) — if the exposed surface gets below the dew point of the surroundings.

For many years, antifog and anti-icing glass has been made by creating on the glass surface a pattern of fine lines of an opaque, electrically conductive material. Screen printing of silver-based frit has been a common method to create patterns, as well as interconnect bus bars. This method has been popular for antifog refrigerator doors and rear windows in automobiles. However, screen printing is cumbersome, often requiring surface preparation and postheat treatments at elevated temperatures. Additionally, soldering of metal lead-outs often requires stringent techniques to avoid damaging the printed pattern, and not even to mention that screen-printed lines are visible and interfere with vision.

Thin-film deposition represents a new technique for making heated glass without compromising transparency and aesthetics. There are a number of metal oxides — also known as transparent conductive oxides (TCO) — that can be both electrically conductive and transparent. These materials can also reflect long-wavelength radiation, providing low-emissivity (low-E) properties to the glass. Examples of this type of materials include fluorine-doped tin oxide (SnO_2: F), Indium-tin oxide (ITO), and thin stacks of oxides and metallic silver. The high demand for low-E glass is responsible for the rapid growth of low-cost tin oxide and metallic silver, as they both compete in the Low-E window market. These materials are deposited by thin-film deposition methods, including thermal deposition during the manufacture of the glass itself, or by physical or chemical vapor deposition (PVD/CVD) onto precut sheets of glass.

Thin-film heated glass is very reliable, as the generated heat is rather evenly diffused over a large surface rather than concentrated in a small area. The uniform radiation, especially at moderate temperatures, is one of this technology's strengths, often requiring less overall energy for equivalent performance. Heated glass adds comfort, condensation control, frost control, energy efficiency, and excellent aesthetics — Fig. 1.

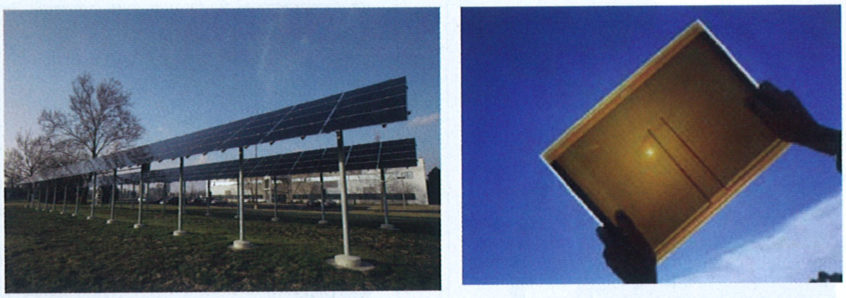

Fig. 2A — Array of thin-film photovoltaic panels (12 kW) made by First Solar LLC, powering an entire building at the University of Toledo Campus, Toledo, Ohio. (Photo courtesy of the University of Toledo, www.utoledo.edu/research.*); B — thin-film photovoltaic glass that uses polycrystalline silicon crystallized by a heating process (courtesy of CSG Solar,* www.csgsolar.com*).*

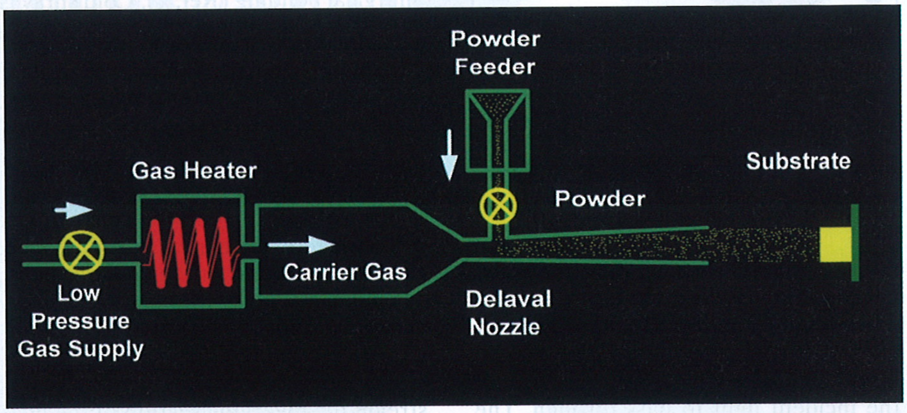

Fig. 3 — Schematic of low-pressure cold spray.

Photovoltaic Glass

Solar energy, available for many years relies on the well-known photoelectric effect displayed by a number of semiconductor materials. Conventional solar cells are made from 200- to 400-µm-thick wafers of pure monocrystalline or polycrystalline silicon, providing energy conversion efficiencies up to 18%. These cells are normally opaque, but by substituting the carrier material by glass as well as spacing the solar cells further apart, they can be made into semi-transparent modules. Unfortunately, the high manufacturing cost of pure silicon, coupled with its relatively low conversion efficiency, have traditionally limited the widespread use of solar cells.

In reality, the exposed surface of a solar cell is effective in converting solar energy only to a few microns in depth; therefore, thin-film deposition of silicon has evolved as a low-cost alternative for the mass production of solar cells — Fig. 2A. Unfortunately, thin-film deposition often yields amorphous silicon that displays conversion efficiencies in the range of 4 to 6%, much lower than crystalline silicon. The low conversion efficiencies, however, did not discourage the massive implementation of thin-film techniques to produce solar cells for many solar-powered commodities such as calculators, watches, and toys. Alternative semiconductor materials continue to be explored, including cadmium telluride (CdTe) and copper-Indium-diselenide ($CuInSe_2$). These materials are claimed to reach conversion efficiencies as high as 12%. Other methods to improve conversion efficiencies include the use of amorphous silicon deposited by chemical vapor deposition onto textured glass surfaces, which is then converted into polycrystalline silicon by controlled heating — Fig. 2B.

Photovoltaic glass windows (Ref. 1) incorporate a semitransparent photovoltaic film on the exterior glass of traditional double-panel glass units. The electric wires extending from the sides of each glass unit are connected to wires from other windows, building up the entire system. The technology is already available in Europe but it is still carving its way into

Fig. 4 — Low-pressure portable cold spray machine. (Photo courtesy of SST™, a division of CenterLine (Windsor) Ltd.)

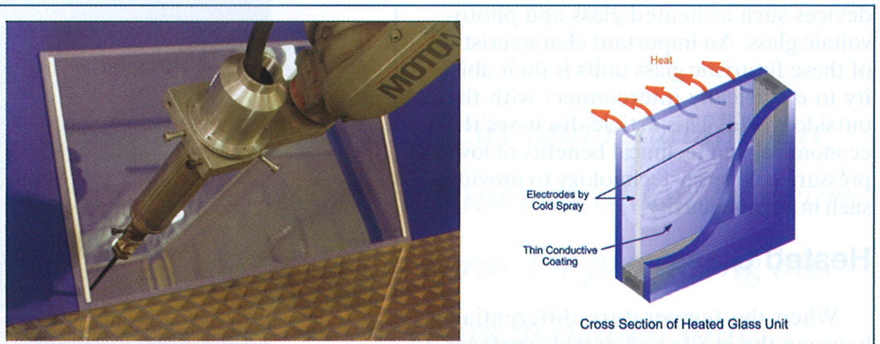

Fig. 5A — Robotic low-pressure cold spray system creating bus bars on architectural glass; B — schematic of a finished heated-glass unit. (Photo courtesy of SST™, a division of CenterLine (Windsor) Ltd.)

the U.S. market through pilot programs by the U.S. Department of Energy. Transparency can be tailored by selectively removing narrow strips of the film using a laser beam, allowing as much as 12% of the incident light to pass through. The view from inside the building looking out is similar to wearing sunglasses. In architectural applications, the cost of photovoltaic glass can be offset by savings in building materials, electricity, and cooling costs.

Creating the Electrical Interconnectivity

In order to make an electrical connection to heated or photovoltaic glass, bus bars are created along two opposite edges of a rectangular sheet. They must be of low electrical resistance, durable, easy to connect to, and well adhering. Bus bars are often created by screen printing of silver frit on the coated glass surface, which calls for special pre- and post- treatments. Many of these secondary processes often limit the conditions under which a given glass sheet can be processed, thus affecting the overall cost of manufacturing.

The Cold Spray Way

Cold spray is an emerging solid-state spraying process in which the coating materials are not melted; instead, the kinetic energy of supersonically accelerated solid particles is converted into interfacial heat upon impact with the substrate, producing a combination of mechanical and metallurgical bonding (Ref. 2). Cold spray is capable of producing thick coatings exhibiting extremely low porosity (< 0.5%), while avoiding oxidation, phase transformations, and tensile residual stresses for a wide selection of metals, cermets, and other material combinations.

In low-pressure cold spraying (Fig. 3), air or nitrogen at 60–140 lb/in.^{2} is heated and directed to a convergent-divergent (DeLaval) nozzle. At the divergent part of the nozzle, the expanding gas accelerates to supersonic speeds, while its temperature sharply decreases to less than 100°C. Powder feedstock is injected downstream the diverging section of the nozzle (Ref. 3), where it gains velocities of up to 600 m/s. Particles charged with this kinetic energy impact the substrate, producing a combination of metallurgical and mechanical bonding.

Low-pressure cold spray systems are compact and economical (Fig. 4), and can be used to reliably spray a number of conductive materials over glass surfaces at very low temperatures, without affecting the glass or requiring any special surface preparation.

Robotic low-pressure cold spray has already been successfully used to create bus bars on heated glass using a proprietary blend of nonferrous materials — Fig. 5. Cold sprayed bus bars proved to exceed the bond strength and electrical resistance requirements set forth by the industry. Since cold spray does not require any special pre- and/or posttreatment, cost savings associated with this process have sparked interest from glass manufacturers. Some of the advantages of cold spray over traditional screen printing processes are as follows:

- Minimum setup
- Low-cost materials
- No pre- or posttreatment
- No masking
- High flexibility and easy changeover
- Consistent bonding properties
- No residual stresses
- Low porosity
- Low oxygen content
- Any glass surface profile
- No special procedure required for lead-free soldering of lead outs

Summary

Low-pressure cold spray is an outstanding alternative solution to silver frit screen printing to produce bus bars in heated and photovoltaic glass. Simplicity and reliability are two of the advantages of low-pressure cold spray, which will facilitate the widespread implementation of functional and environmentally friendly glass technologies in the marketplace.◆

Acknowledgments

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