

SPRAYTIME®

Published by *The International Thermal Spray Association*
Volume 14, Number 4 Fourth Quarter 2007

Cryogenic Nitrogen Gas Cooling for Thermal Spray Coatings

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The current industry trend towards more heat intensive processes in thermal spray applications has exposed the inadequacy of current cooling solutions. It has highlighted the need for better thermal management of coated parts. This article describes a novel cooling approach that uses a 2-phase, cryogenic nitrogen vapor to help eliminate waste, plus improve productivity and part quality.

Current Process

HVOF thermal spray is widely used for coating critical wear parts like landing gear, bearing races, valves and turbine components. Generally, fully or partially molten metal, composite, or ceramic droplets are propelled from a gun or torch onto the workpiece. Multiple passes are required to build up the coating, since each pass only deposits ~ 0.0002 in - 0.0005 in thickness of material. A significant amount of thermo-kinetic energy is required to deposit a dense coating onto the work surface—and a portion of this energy, manifested as heat, is absorbed by the workpiece. Improper temperature control during thermal deposition frequently leads to coating and workpiece overheating, thermal deformation and degradation of substrate material, and damaging stresses due to a mismatch of thermal expansion coefficients between the coating and substrate. When damage occurs through overheating and thermal stress, delamination of the coatings can occur in service.

Consequently, thermal management of the workpiece is extremely critical during the spray deposition process. Compressed air jets are the primary cooling method for most HVOF thermal spray operations; however, air cooling is usually insufficient and the oxygen, residual moisture and hydrocarbons present in the cooling air are often detrimental to the coating quality. In spray operations involving tighter temperature control, air cooling is usually inadequate and manufacturers are often forced to introduce breaks in the process cycle so that the accumulated heat is dissipated to the ambient environment. The spray gun is moved away from the part but continues firing during the

inter-pass cooling breaks, resulting in wasted feed powder, process gas, and booth time.

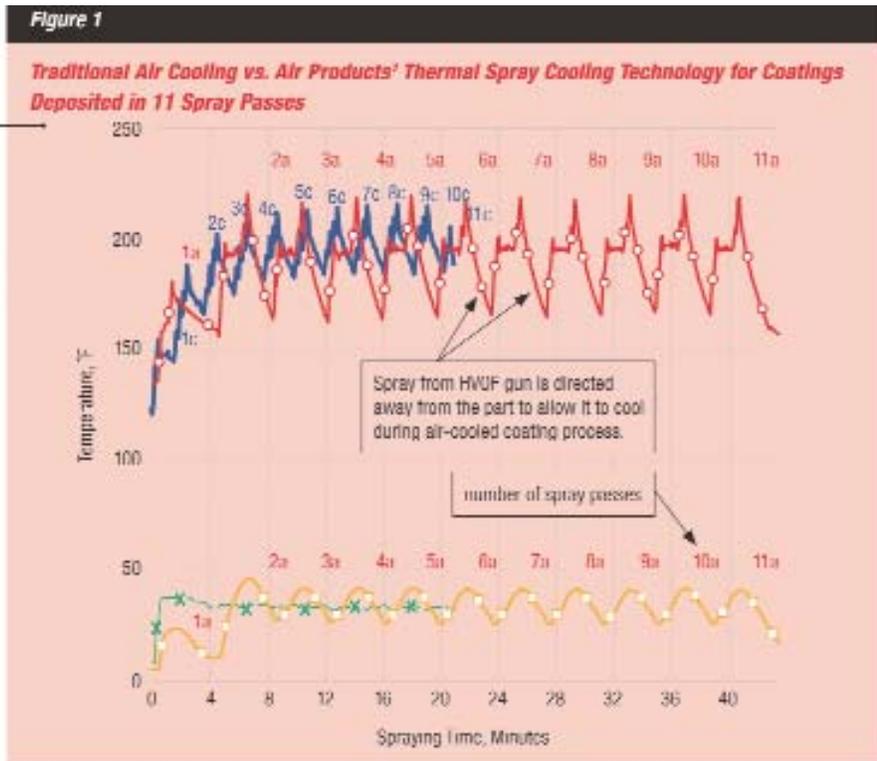
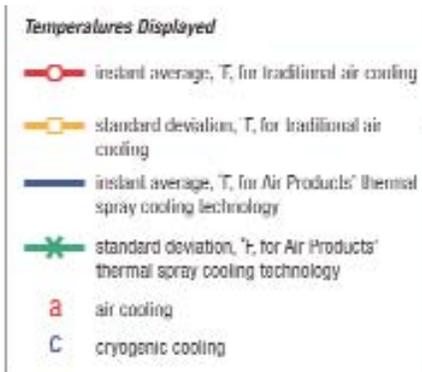
Another issue that affects productivity in spray coating operations is the set-up time for masking and de-masking. It is important to mask certain areas of the part, where the coating might not be needed. The coating of these areas might be undesirable (it may interfere with the mechanical working of the component), unneeded, or simply, uneconomical. In these cases, it is critical to provide an effective barrier to coating for these areas. Metal plates (shadow plates) are often used to protect these areas, as are masking tapes.

The desirable aspects of a masking tape are flexibility, ease of application and removal, quick clean-up and extended useful life. There is a wide variety of masking tapes available today with materials of construction ranging from fiberglass and metals to polymer and silicone rubbers. Metal tapes are usually difficult to make and install, while the fiberglass and polymer tapes are easy to install but difficult to remove and require extensive post-spray cleaning. Inadequacy of air cooling and build-up of temperature is the primary reason for tape degradation, e.g. thermal decomposition, hardening, or tape embrittlement.

A New Approach to Cooling

The search for a more efficient cooling approach to generate better coating properties, as well as to improve the productivity of HVOF spray coating operations has led to the development of cryogenic nitrogen gas cooling. Although cryogenic cooling methods offer a significant enhancement in the ability to remove heat quickly, they are rarely used in the thermal deposition coating industry due to the risk of non-uniform cooling, which results in variable levels of residual stresses at the substrate/coating interface and consequent issues of coating delamination and spalling. Carbon dioxide (CO₂) cooling has been used by the industry with mixed success. While CO₂ has higher heat capacity compared to nitrogen — its heat removal rate is constrained by the smaller temperature differential (CO₂ has a boiling point of -78.5°C, while cryogenic nitrogen boils at -196°C). CO₂ also has a tendency to form undesired, solid deposits at the target surface whenever higher cooling rates and correspondingly higher gas flow rates are required.

Cryogenic nitrogen gas cooling has been shown to



significantly improve productivity over conventional air-cooled processes. Figure 1 shows actual process data comparing the two cooling methods during deposition of a WC-Co-Cr coating on an aerospace landing gear. By eliminating the inter-pass cooling breaks, the cryogenic vapor cooling system shortened the spraying time by 50%, plus it reduced wasted feed powder and process gases. The nitrogen cooling system also allowed for a much tighter temperature control ($\pm 20^\circ\text{F}$) and a significantly smaller standard deviation in workpiece temperature during coating operation. Subsequent characterization of the air-cooled and nitrogen-cooled samples

Air Products' novel thermal spray cooling technology delivers exceptional results. This graph shows actual process data for spraying aircraft landing gear with traditional air cooling compared to our nitrogen cryogenic vapor cooling system. With the Air Products thermal spray cooling technology, the part's temperature was maintained within a much tighter range during the spray operation. In addition, it halved the spraying time and the amount of powder and process gases consumed—plus improved productivity.

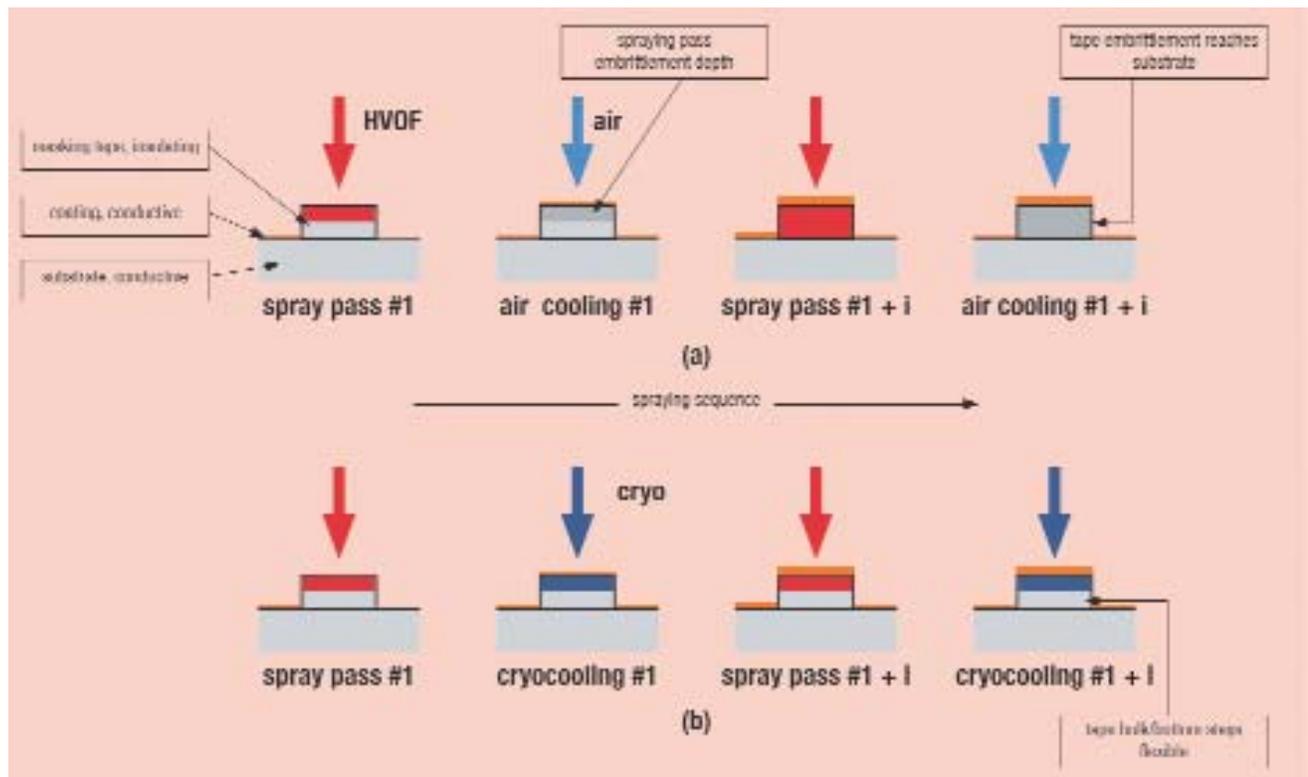


Figure 2: Effects of cooling on silicone-based masking tapes during HVOF spray
 (a) Air cooling (b) Cryogenic nitrogen vapor cooling

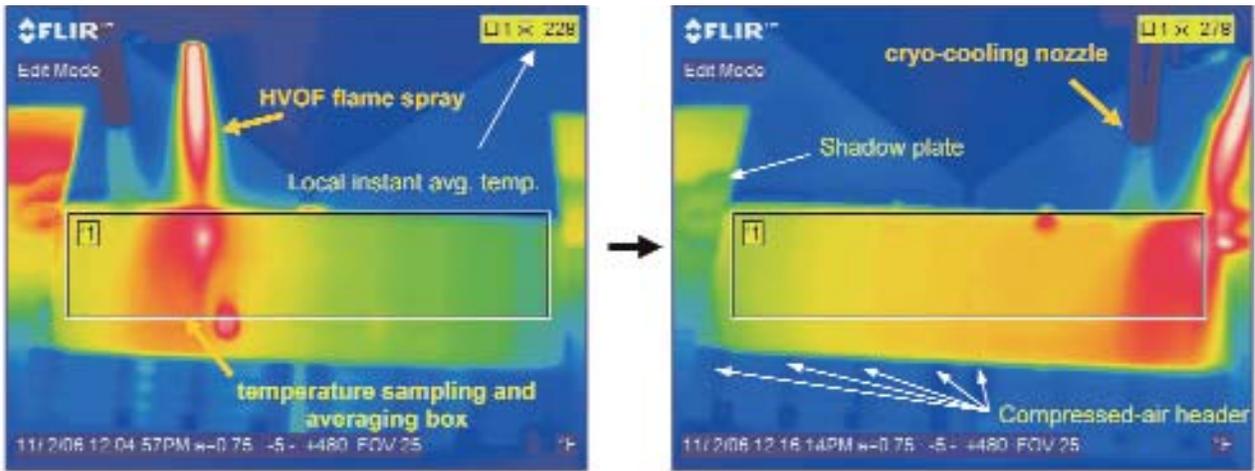


Figure 3: Thermal profiles at various stages in the coating process, showing effective temperature control of the coated surface with cryogenic cooling (a) Start of spraying pass (b) End of spraying pass

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show that the bond-strength, hardness and surface roughness of the as-sprayed coatings were essentially unchanged, while micro-porosity was reduced from 0.2 to 0.05%. The nitrogen-cooled sample also retained the substrate hardness (420 HV in the case of heat-treated 4340 steel) better than



Figure 4: Air Products Nitrogen Spray Cooling System
Air Products' cryogenic spray nozzle installs easily on any thermal spray gun to help cool parts twice as fast as air cooling alone, which allows thermal spray operators to work faster and more efficiently with less wasted powder, process gas, and booth time.

the air-cooled (395 HV) and non-cooled (390 HV) samples. In addition, oxygen pick-up and carbon-loss in the coating were the lowest for the nitrogen-cooled sample. In limited tests with cryogenic cooling, involving WC-Co-Cr powder, deposition efficiency was shown to increase by an average of 10 to 15% over conventional air cooling and by more than 30% over non-cooled samples.

An additional benefit of the cryogenic nitrogen vapor cooling system is the time and cost savings in the masking process. The cryogenic gas provided instant cooling of the hot top layer of the mask, avoiding heat build-up and preventing the heat from reaching the bottom of the tape. As a result, the tape bulk stayed flexible and could be removed quickly after the spray operation with a putty knife, leaving a clean residue-free surface. It could even be re-used several times. Figure 2 schematically shows the effectiveness of cryogenic cooling to prevent progressive thermal degradation of silicone-based masking tapes.

The cryogenic nitrogen vapor system efficiently and uniformly cools thermally sprayed coatings by monitoring the temperature of the coating and varying the cooling intensity to match the heat generated in the spraying process. The temperature feedback system can use a variety of inputs, including single-point IR sensors, 2-D thermo-imaging IR cameras, and contact thermocouples. The PLC-controlled cooling system maximizes cooling efficiency by automatically switching cooling modes between room temperature, nitrogen gas, liquid/gaseous nitrogen mixed flow, and 100% liquid nitrogen based on user-defined temperature ranges. Discharged from a spraying nozzle or multiple sprayers, the liquid nitrogen is atomized to form rapidly boiling, microscopic droplets that turn into cryogenic nitrogen vapor within a short distance from the discharge point. This prevents undesired "wetting" of the coated surface. In addition, multi-zone cooling control algorithm used allows individual cooling nozzles to independently switch between the cooling modes based on instant average and time-averaged temperature feedback.

Figure 3 shows the thermal profiles at various stages of the coating process. The part temperature history can also be recorded and archived for future audit purposes.

The new Air Products' patent-pending, thermal spray cooling technology (Figure 4) is the industry's only cryogenic nitrogen cooling process. It has provided productivity benefits in a range of HVOF coating applications, involving aerospace parts, construction equipment, and rolls. Nitrogen cooling has also been proven to be an effective and economical solution for heat-intensive spraying processes (high pressure liquid fuel HVOF systems and high spray rates). The use of cryogenic vapor as a supplement to existing air cooling and variation of cooling intensity with heat input helps ensure the most economical use of the cryogenic coolant. Cryogenic vapor cooling has also provided important part quality benefits, like preservation of substrate properties, minimized coating oxidation and reduced residual stress gradient between the coating and the substrate.

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